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Design and Simulation of eVTOL Aircraft Thermal Management System

This paper focused on designing a thermal management system (TMS) for a parallel hybrid electric (PHE) XV-15 tiltrotor aircraft used in urban air mobility (UAM) applications. The TMS is integrated into the aircraft system to assess its impact at aircraft and mission levels. Both liquid cooling and air-cooling TMS, along with using phase change materials (PCMs) for heat storage, were designed and assessed. Two liquid-cooling configurations, series and parallel, were evaluated, with the series configuration proving more effective in the considered test cases. The study compared hover and cruise conditions to determine optimal design point for the liquid-cooling TMS. Designing for hover resulted in about fourfold increase in the TMS penalty in fuel burn during cruise. Designing for cruise, on the other hand, proved infeasible to comply with the thermal management requirements during hover. Two approaches were explored to address this: Approach A involves adding PCMs as a heat storage system and approach B entailed redesigning the TMS with the heat load at off-design conditions for the inverter and motor. Both approaches resulted in a 24% and 46% increase in the TMS penalty in fuel burn compared to the design that solely considering cruise condition, respectively. The assessment of the designed aircraft systems, integrating the TMS for the considered test cases, revealed that the liquid-cooling TMS designed at cruise condition with Approach B emerged as the optimal design, showcasing a 42% improvement in fuel burnt per payload compared to the air-cooling TMS at the mission level. [DOI: 10.1115/1.4066820]

1 Introduction

The increasing population density in urban areas has led to growing concerns over time wastage and emissions resulting from traffic congestion, impacting both public convenience and environmental sustainability. Urban air mobility (UAM) emerges as a promising solution within the aviation industry, presenting a novel transportation mode for addressing these challenges [1,2].

This application envisions the transportation of up to 15 passengers through short and frequent flights covering a range of 50 nautical miles or less. It relies on the vertical takeoff and landing (VTOL) capability inherent in rotorcraft configurations. Depending on the size and mission requirements, hybrid or fully electric propulsion systems are considered, aiming to minimize the environmental footprint [3]. Despite the broad range of UAM architectures observed in various studies and industrial demonstrators, the limited power and energy density of current electric systems constrain fully electric configurations to smaller passenger capacities and lower endurance (e.g., Refs. [1–3]).

In the case of conventional gas turbine engines, the greater part of losses is expelled in the form of heat through the engine exhaust. However, in hybrid or fully electric configurations, the electric components generate low-grade waste heat that cannot be dissipated in a similar manner. Additionally, the strict operating temperature

requirements of the electric components necessitate effective thermal management systems (TMS) to ensure operation within appropriate temperature limits [4].

Conventionally, ram-air-based or liquid-cooling systems are commonly employed for the TMS of electric powertrain due to their simplicity as noted in previous studies (e.g., Refs. [4–11]). Chapman et al. [4] developed liquid-cooling-based TMS for three electrified aircraft propulsion concepts, establishing generalized TMS sizing relations. In a following work [5], the development and optimization of a liquid-cooled TMS for the turbo-electric tilting aircraft application the discussed. The transient analysis of the designed TMS is conducted considering 4-min hover from hot day rest. The development of a liquid-cooled TMS for a six-passenger parallel hybrid electric (PHE) quadrotor aircraft is discussed in Ref. [6]. A performance map-based method is used for the heat exchanger design. The TMS design is evaluated across various mission points without undergoing a comprehensive dynamic full mission analysis.

Kellermann et al. [8] designed a ram-air-based TMS with air-coolant heat exchanger and liquid-cooled cold plates, for a 180-passenger short-range partial-turbo-electric aircraft. The study underscored the importance of ensuring off-design performance of the designed TMS, as the puller fan is required to comply with the thermal management requirement for the most challenging off-design condition. The impact of the designed TMS was assessed at the aircraft level for multipoint simulations but not at the mission level.

The work of Rheume et al. [9–11] presented a liquid-cooling TMS design methodology for a PHE propulsion system of a

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The existing literature lack sufficient quantification or discussion on the integrated design and assessment of TMS for PHE rotorcraft applications at the mission level, resulting in a notable knowledge gap. Additionally, there is a limited discussion regarding the comprehensive impact of the designed TMS at the aircraft level. Furthermore, a comparison between applicable cooling technologies is not yet addressed.

This paper aims to present a design methodology for a liquid-cooled TMS for the PHE civil rotorcraft application reported in Ref. [12], which is recognized as more effective than air-cooling, and assess its integration impact at both the aircraft and mission levels. The sizing condition for the TMS is established based on a mission comprising two consecutive 150 km range missions without any recharging in between. The mission represents the operating conditions expected for frequent short missions in UAM applications and is expected to strain the thermal management system as discussed in Ref. [12]. An air-cooled TMS is designed for the identical condition to facilitate a comparative analysis. Additionally, a one-engine inoperative (OEI) certification point condition is considered by incorporating PCMs as a heat storage system for such a condition.

The design and assessment approach for the integrated thermal management system of a PHE tiltrotor aircraft is outlined in Fig. 1. The aircraft system is designed according to the predetermined hybrid-electric propulsion system (HEPS) optimized for the aircraft

Subsequently, the propulsive power requirement profile for the design mission is determined by employing a rotorcraft model that considers the specified gross weight. Following this, the optimal power management strategy (PMS) is identified, aiming to minimize energy consumption across mission phases. The heat load profile for the electric powertrain during the mission is then derived based on the optimized PMS. Two design points are selected for the TMS design: (A) Hover, representing peak heat load condition, and (B) Cruise, reflecting nominal heat load condition. Both air-cooled and liquid-cooled TMS models are designed and integrated with the aircraft model for a comprehensive performance and feasibility assessment at both the aircraft and mission levels.

The modeling approach for the rotorcraft and HEPS has been extensively discussed by the authors in Ref. [12]. In alignment with this established methodology, a brief overview is provided in the respective section, with explanations for the modifications to the design.

2.2 Hybrid-Electric Propulsion System. The HEPS model is developed by utilizing Simcenter Amesim software as the modeling platform. Dynamic models sourced from the “Gas Turbine,” “Electric Motor and Drives,” and “Electric Storage” Simcenter Amesim libraries are used to build the integrated HEPS model, facilitating transient simulation throughout the flight mission [20,21].

The PMS determines the required propulsive power from each electric powertrain and gas turbine engine during specific mission phases. Similar to the prior study, the PMS optimization is conducted through the Simcenter Amesim software using the Nonlinear Programming Quadratic Line search algorithm [12]. The optimization incorporates a battery minimum state of charge (SOC) constraint of 20% to prevent irreversible damage from depth discharges to the battery electrodes [22].

By scaling down the core gas turbine for a given power ratio, performance and weight advantages can be achieved, as discussed in



Table 1 KPIs of the Electric powertrain [4,14,26–28]

Components	Type/ C_p determination	Power/Energy density (kW/kg)/(Wh/kg)	Efficiency (%)	Operating temperature limit (°C)
Motor	Permanent magnet motor/copper as baseline material (winding conductor)	8	96%	80
Inverter	Silicon-based power electronics/silicon as baseline material	8	98%	60
Battery	Lithium-ion battery/provided in Simcenter Amesim software	250	Variable	45 (up to 57 for 10 mins operation)

Refs. [13,24]. This downscaling is feasible because the propulsive power demand from the gas turbine engine is reduced by the introduction of the electric powertrain. However, a tradeoff study on the potential gas-turbine lifting benefits due to the reduced propulsive power demand should also be considered. Following the approach employed in Ref. [12], the gas turbine engine is scaled down by using a simple correlation with the design mass flowrate, per the following equation:

$$m_{GT} \propto (\dot{m}_{design})^{1.45} \quad (1)$$

However, downscaling the gas turbine engine would lead to deterioration in the efficiency of its components. The reduction in component efficiency is estimated through simple correlation with the design mass flow reduction rate from [25].

2.2.2 Electric Powertrain. The electric components are assumed as homogeneous bodies for specific heat capacity calculations, and their weights are estimated based on the methodologies outlined in Ref. [24]. The key performance indicators (KPIs) employed for the components comprising the electric powertrain are summarized in Table 1 [4,14,26–28]. It is important to note that motor and inverter efficiencies are assumed to be constant throughout the mission, while battery efficiency varies based on operating conditions such as the SOC and voltage variation. A peak battery operating temperature limit denoted in parentheses represents the permissible value for short duration of up to 10 min [4].

2.3 Thermal Management System Design and Integration With the Platform. The TMS design and integration with the tiltrotor model process are discussed herein. The designed TMS incorporates two widely used cooling techniques: air-cooling and liquid-cooling.

In both systems, a cold plate serves as the heat acquisition device for each electric component. Subsequently, the acquired heat is transferred to the final heat sink (air) and removed from the system. Since the air-cooling system utilizes the air as a coolant, eliminating the need for an additional device for heat transfer to the final heat sink. On the other hand, the liquid-cooling system necessitates an air-coolant heat exchanger to dissipate the acquired heat from the system.

Furthermore, the inclusion of PCMs as heat storage systems is assessed as part of the TMS for certain test cases. Given the distinct operating temperature limits among electric components, various types of paraffins are considered, and their properties are summarized in Table 2 [29–31]. Paraffins are considered suitable materials for heat of fusion storage due to their availability in a broad temperature range. They are distinguished by their safety, reliability, predictability, cost-effectiveness, and noncorrosive

properties [29]. The designed PCM heat storage system has two key assumptions: first, ensuring a sufficient heat transfer rate to the PCMs during the cooling, and second, considering the PCMs as thermally insulated when the heat storage system is not in use.

The PCM weight is estimated by using the latent heat of fusion and its heat capacity up to its melting temperature, as outlined in the following equation:

$$m_{PCM} = \frac{Q_{store} - m_{PCM} \cdot c_{p,solid}(T_{melting} - T_{initial})}{LHF} \quad (2)$$

2.3.1 Air-Cooling Thermal Management System. The design approach for the air-cooling TMS design is established upon prior analyses, incorporating modifications to address the identified limitations [12]. The air-cooled cold plate is designed by employing a semi-empirical method proposed in Ref. [32]. This method involves assessing the performance of cooling fins and determining the temperatures at various locations on the fins, considering a given cooling air temperature and heat load. A plain fin geometry is selected to minimize pressure drop across the cold plate, given the absence of a puller fan in the designed configuration. The optimization algorithm is employed in the design of the air-cooled cold plate [33]. In this approach, cold plate dimensions are treated as variables, with fin and base plate thickness kept constant. The objective is to minimize the weight of the cold plate while complying with the surface temperature and pressure drop limits.

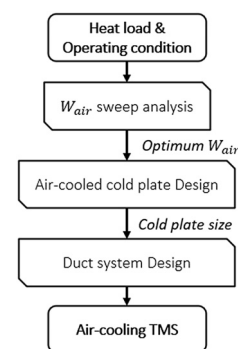
The air-cooling TMS design process is depicted in Fig. 2. For a given heat load and operating condition, a sweep analysis is first conducted to identify the optimum air mass flowrate that results in the minimum weight. Subsequently, the air-cooled cold plate is designed based on this determined air mass flowrate.

In the previous study, the connection between the dimensions of the designed air-cooled cold plate and the duct system was omitted, resulting in an impractical overall design of the air-cooled TMS.

Consequently, the updated duct system includes a connecting duct between the diffuser-and-nozzle and the cooling duct. This addition is essential to accommodate the dimensions of the air-cooled cold plate while ensuring the desired air mass flowrate across the system. The dimensions of the cooling duct are determined based on the maximum dimensions of the cold plates, considering the maximum width, maximum height of the fins, and the total length of the cold plates. To minimize the impact of the duct walls, slight margins (0.05 m and 0.1 m) are applied to the width and height of the

Table 2 PCM properties [29–31]

Component	Battery	Inverter	Motor
Paraffins	C ₂₂ H ₄₆	C ₂₆ H ₅₄	C ₃₄ H ₇₀
$T_{melting}$ (°C)	44	56.3	75.9
LHF (kJ/kg)	249	256	269
ρ (kg/m ³)	778	800	800
$c_{p,solid}$ (kJ/kg/K)	1.51	1.80	1.85
$c_{p,liquid}$ (kJ/kg/K)	2.38	2.37	2.40

**Fig. 2 Air-cooling TMS design process**

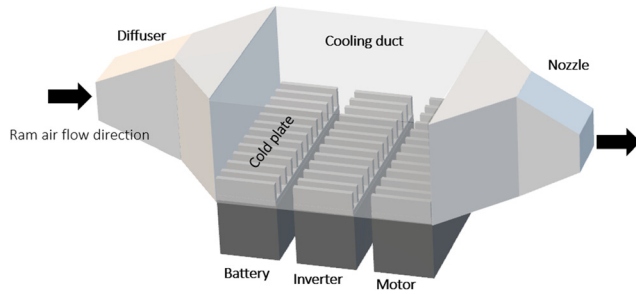


Fig. 3 The air-cooling TMS design schematic

cooling duct, respectively. The duct system's design incorporates an 8-degree diffuser angle and a 30-degree nozzle angle, with a fixed area ratio of 2 [8,34]. The length of the connecting duct is set at 0.1 m. The weight of the duct system is calculated, assuming it is made of aluminum. Additionally, the series configuration is chosen to minimize the size of the duct system, and the battery cold plate is positioned at the forefront due to its stringent operating temperature limit. The air-cooling TMS design schematic is presented in Fig. 3.

2.3.2 Liquid-Cooling Thermal Management System. Figure 4 illustrates the design schematic of the liquid-cooling TMS. The liquid-cooled cold plates are used to acquire heat from each electric component. The design of the cold plate employs a comprehensive approach, incorporating a thermal-hydraulic model and an effective-number of transfer units (ϵ -NTU) model that derive the relationship between heat exchanger volume, heat transfer coefficients, and pressure drop, as detailed in Ref. [35].

An offset-strip fin geometry is selected for its superior heat transfer efficiency compared to plain fin geometry. Although it typically results in higher pressure drops, this is no longer a critical limitation in the design due to the presence of a dedicated coolant pump [36]. To achieve a more compact cold plate design, the offset-strip fin geometry with specific dimensions (1/9–22.68) is selected [37]. As for the coolant, an ethylene glycol–water mixture is used, a commonly used coolant in modern TMS [38].

The cold plate is designed by varying the width and length, keeping the height fixed based on the predefined fin geometry (1.1 cm). This is conducted to achieve minimum weight while ensuring the specified surface temperature limit. Note that the pressure drop across the cold plate is converted into an estimated pump weight to ensure the pressure drop remains within a reasonable range.

The air-coolant heat exchanger is built-in to transfer heat from the coolant to the air and release it from the system. A plate-fin type heat exchanger is selected for its effectiveness and compactness [36].

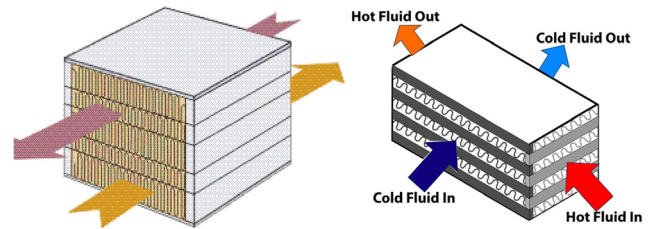


Fig. 5 Counter- and cross-flow heat exchanger [39,40]

Even though crossflow heat exchangers typically have an effectiveness range of 50–75% (compared to 75–85% for counterflow heat exchangers), the crossflow design is chosen to simplify integration. In a counterflow setup, intricate connections for each layer are needed to prevent mixing of air and coolant streams, as illustrated in Fig. 5 [39,40]. Both the air and liquid coolant layers in the heat exchanger follow the same offset-strip fin geometry as the cold plate design (1/9–22.68) [37]. The employed air-coolant heat exchanger design approach is based on [35] as well. Note that the air-duct system is designed to accommodate the width and height of the air-coolant heat exchanger, while the coolant line design is not considered in this study.

A puller fan and coolant pump are integrated to efficiently propel air and circulate coolant throughout the system. The weight of the puller fan and the coolant pump is estimated based on the displacement-weight correlation outlined in Ref. [5]. The ideal power consumption of these components is calculated in accordance with the following equations: [5].

$$P_{\text{pump}} = \frac{W_{\text{coolant}} \Delta P_{\text{coolant}}}{\rho_{\text{coolant}}} \quad (3)$$

$$P_{\text{fan}} = W_{\text{air}} \times c_{p,\text{air}} \times (T_{\text{out,fan}} - T_{\text{in,fan}}) \quad (4)$$

The design tool for liquid-cooling TMS is developed by incorporating an optimization algorithm targeting to minimize the fuel burn penalty associated with both weight and power consumption of the designed TMS [33]. The correlation between the fuel-burn penalty is derived through sensitivity analysis of the gas-turbine engine model against both the addition in propulsive power requirement and gross take-off weight (GTOW) of the aircraft.

As illustrated in Fig. 4, two feasible configurations of liquid-cooling TMS are designed and comparatively assessed to understand the impact of configuration selection.

Table 3 provides a summary of the liquid-cooling TMS design optimization approach for both configurations. It is evident that the

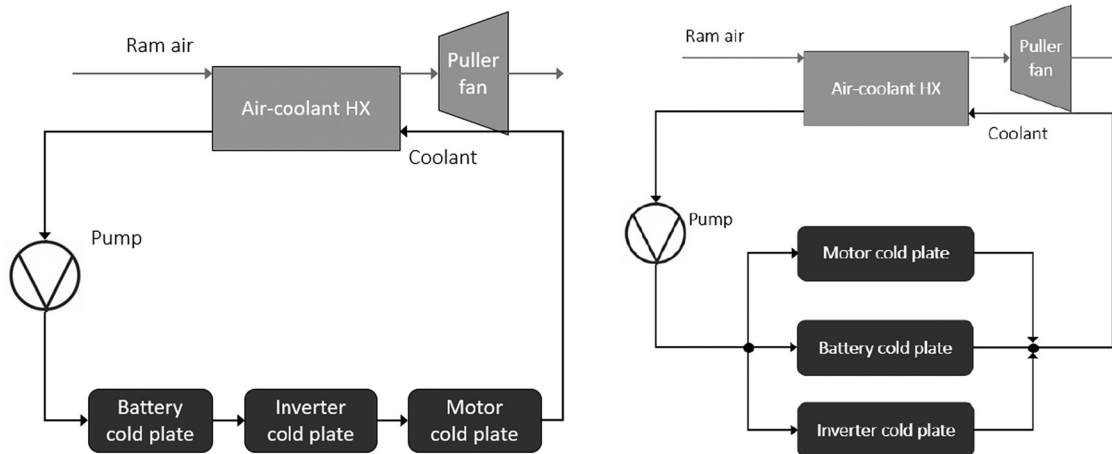


Fig. 4 The liquid-cooling TMS design schematic – series (left); parallel (right)

Table 3 The liquid-cooling TMS design optimization approach

Objective	min (Penalty in $W_{f,TMS}$)	
	Series	Parallel
Variables	$*W_{coolant}$ $*Temperature\ pinch\ (T_{air,in} - T_{coolant,out_HX})$ $*W_{air}$	$*W_{coolant}$ $*Temperature\ pinch\ (T_{air,in} - T_{coolant,out_HX})$ $*W_{air}$ $*W_{coolant,batt}/W_{coolant}$ $*W_{coolant,inv}/W_{coolant}$
Constraints	$*T_{coolant,out_HX} < (T_{oper,batt,limit} + 3\ ^\circ C)$ $*0.55 < \varepsilon_{HX} < 0.75$ $*T_{surface} < T_{oper,limit}$	$*T_{coolant,out_HX} < (T_{oper,batt,limit} + 3\ ^\circ C)$ $*0.55 < \varepsilon_{HX} < 0.75$ $*T_{surface} < T_{oper,limit}$ $*(W_{coolant,mot}/W_{coolant}) > 0.05$

Table 4 Fuselage cabin dimensions of XV-15 aircraft [41]

Interior dimensions:	
Length (m)	3.99
Width, maximum (m)	1.52
Width, at floor level (m)	1.22
Height, maximum (m)	1.52
Height, underwing (m)	1.37

parallel configuration would necessitate more computational resources as it involves a greater number of variables in the optimization process.

2.3.3 Integration With the Platform. The XV-15 aircraft dimension data are taken into consideration for the integration of the designed TMS with the platform. Considering the convergence toward a greater width in the cold plate design for minimizing weight and pressure drop, the optimization process constrains the width to a maximum of 1.45 m, aligning with the fuselage width specified as 1.52 m in Table 4 [41]. Similarly, the air-coolant heat exchanger design is optimized with a maximum coolant side length of 3.5 m, aligning with the specified fuselage length [41].

In addition to the weight and power consumption penalties, it is essential to account for the drag power induced by the air-duct system. In this study, the air-duct system is assumed to be integrated with negligible exposure to the surroundings, and the impact of additional wetted area is not considered. The spillage drag power at the diffuser inlet and the drag power at the nozzle outlet are calculated using Eqs. (5) and (6) suggested by Kellerman et al. [8]

$$P_{spill} = K_{spill} [W_{air}(v_1 - v_0) + A_1(p_1 - p_0)] \times v_0 \quad (5)$$

$$P_{nozzle} = W_{air}(v_{exit} - v_0) \times v_0 \quad (6)$$

3 Definition of Test Case

The aircraft selected for this study is modeled after the NASA XV-15 [19], designed and validated in Ref. [13]. It is a civil rotorcraft that integrates high-speed cruise and vertical takeoff and landing capabilities, making it suitable for air taxi operations. The baseline configuration is equipped with two turboshaft engines mounted on nacelles, extensively detailed in Refs. [19,41]. It is important to note that the study defaults to the hot day condition (ISA 25) to ensure the TMS performance in extreme conditions. The subsequent discussion outlines the test case missions assessed in this study.

3.1 Hybrid-Electric Propulsion System Design. The PHE tiltrotor variant is designed based on the framework presented in Ref. [13], and Table 5 outlines the top-level parameters of the

Table 5 Electric powertrain sizing results

Motor and Inverter	
Maximum power rating (kW)	1210
Optimum power ratio	0.79
Maximum motor power (kW)	254.1
Motor weight (kg)	31.8
Inverter weight (kg)	31.8
Battery	
Energy consumption [kWh]	1005.6
Optimum energy ratio	0.85
Battery energy [kWh]	150.8
Battery weight [kg]	488.3

optimized electric powertrain. The energy consumption is based on the XV-15 aircraft's design range mission (700 km), while the maximum power rating is a requirement for the aircraft. The optimum power and energy ratio is derived by optimizing the HEPS for energy efficiency with the assumption of a constant TMS density [13]. Note that Danis et al. [28] employed the power ratio of 0.84 in their study for this aircraft

$$Power\ ratio = \frac{P_{GT}}{P_{total}} \quad (7)$$

$$Energy\ ratio = \frac{E_{GT}}{E_{total}} \quad (8)$$

3.2 Certification Point Condition. To ensure the aircraft system can handle engine failures, a 5-min contingency hover is applied to design the TMS in compliance with certification point condition requirements [28]. The PHE tiltrotor is set to operate at its maximum power rating during the mission, utilizing the maximum available motor power [13].

For the certification point condition, the PCM heat storage system is utilized to address the thermal management requirement for this specific mission. The results are outlined in Table 6 [12].

3.3 Thermal Management System Design and Assessment Mission. The mission selected to design and evaluate the capabilities of the TMS involves two consecutive 150-km range missions

Table 6 TMS design results - certification point condition

	Batt	Inv	Mot
Heat load (kJ)	8224.0	1617.3	3169.9
SOC _{initial} (%)		40%	
$T_{initial}$ (°C)		$T_{melting,PCM}$	
$W_{PCM,OEI}$ (kg)	36.33	6.95	12.96
$W_{PCM,total}$ (kg)		59.01	

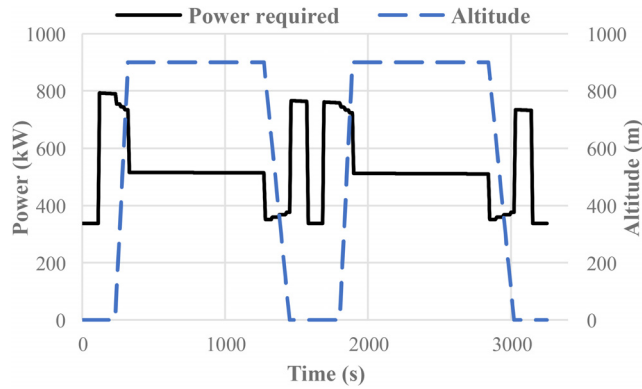


Fig. 6 TMS design and assessment mission profile – 2 consecutive 150 km range and 6000 kg GTOW

Table 7 Optimized PMS for the TMS design and assessment mission

Mission phase	Power ratio	
	First part	Second part
Idle	1.00	1.00
Hover	0.73	0.74
Climb	0.75	0.72
Cruise	0.78	0.78
Descent	0.87	0.87
Hover	0.74	0.76
Idle	1.00	1.00

without recharging in between and with a GTOW of 6000 kg. Figure 6 depicts the propulsion power requirement and altitude profile for this specific mission.

The optimum PMS is identified for minimum energy consumption without considering the TMS penalty (Table 7).

Figure 7 depicts the waste heat profile of the electric powertrain components. The essential waste heat values for each electric powertrain component are summarized in Table 8, serving as the designated design points for the TMS.

4 Results

The following discussion covers the results of the specified test case for the TMS design in both air-cooling and liquid-cooling configurations. Subsequently, the overall performance of the designed PHE tiltrotor aircraft with an integrated TMS for the

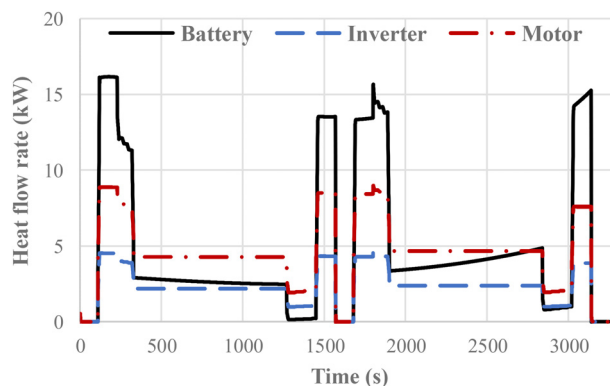


Fig. 7 Waste heat profile of the electric powertrain in the TMS design and assessment mission

Table 8 Waste heat released by the electric powertrain components

	Battery	Inverter	Motor
Q_{peak} (kW) (hover)	16.2	4.6	9
Q_{nominal} (kW) (cruise)	4.9	2.5	4.8

Table 9 Air-cooling TMS design results

	Batt	Inv	Mot
W_{air} (kg/s)		2.995	
Width (m)	1.45	0.94	1.00
Length (m)	1.00	0.24	0.10
$m_{\text{cold plate}}$ (kg)	57.38	4.81	3.38
m_{PCM} (kg)	28.8	7.4	13.0
m_{duct} (kg)		50.1	
P_{duct} (kW)		25.21	
m_{TMS} (kg)		164.9	
Penalty in W_f (g/s)		0.323	

selected design conditions is assessed and discussed at the mission level.

4.1 Air-Cooling Thermal Management System. In the air-cooling TMS, the air-cooled cold plates are designed for the cruise condition, and the PCMs are a heat storage system to address the thermal management requirements during the mission phases with limited ram-air. The designed air-cooling TMS results are presented in Table 9. The weight of the TMS designed for the battery is notably heavier than other electric powertrain components, primarily due to the stringent operating temperature limit.

The electric powertrain components meet the specified temperature requirements, as depicted in Fig. 8.

4.2 Liquid-Cooling Thermal Management System. The liquid-cooling TMS is designed at both the hover and cruise conditions to determine the optimal design point. Concurrently, two configurations, series and parallel, are designed and assessed. The designed liquid-cooling TMSs are rated at off-design conditions to verify thermal management performance. If the designed system fails to comply with operating temperature requirements at off-design conditions, adjustments are made to the air and coolant mass flow rates.

4.2.1 Hover—Design Point. Table 10 presents the sizing results for both series and parallel liquid-cooling TMS designed at the hover condition. The designed TMS weights show a significant reduction compared to the air-cooling TMS. It is important to note that the power consumption of the designed TMS is underestimated, as the

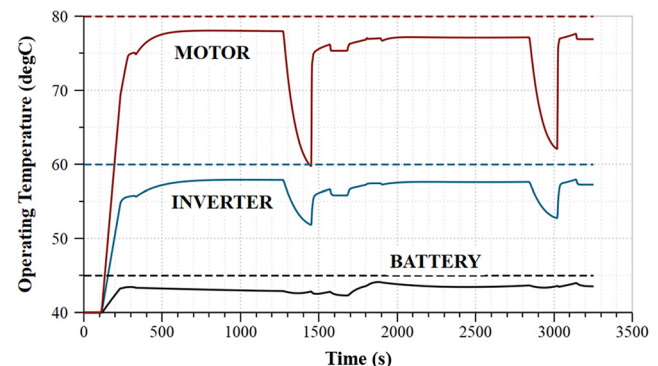


Fig. 8 Operating temperature profile of the air-cooling TMS (dashed lines: limits)

Table 10 Liquid-cooling TMS design results (HOV) – hover condition

Series			Parallel			
Cold plate						
	Battery	Inverter	Motor	Battery	Inverter	Motor
W_{coolant} (kg/s)		0.46		0.58	0.12	0.08
Weight (kg)	8.62	1.21	0.19	8.58	1.19	1.38
Width (m)	0.78	0.28	0.27	0.77	0.13	0.12
Length (m)	1.02	0.40	0.06	1.02	0.81	1.02
Auxiliary components						
	Pump	Puller fan	Air duct	Pump	Puller fan	Air duct
Weight (kg)	4.66	0.84	7.77	8.57	1.05	6.23
Power (kW)	0.004	17.92	—	0.009	22.04	—
Pressure ratio	—	1.11	—	—	1.11	—
Air-coolant heat exchanger						
ε_{HX}	W_{air} (kg/s)	Weight (kg)	ε_{HX}	W_{air} (kg/s)	Weight (kg)	
0.74	1.80	53.15	0.75	2.28		39.27
Width (m)	Length (m)	Height (m)	Width (m)	Length (m)	Height (m)	
3.49	0.18	0.05	2.25	0.13		0.08
Design summary						
			Series		Parallel	
Total weight (kg)			76.45		66.26	
Total power (kW)			17.93		22.05	
Penalty in W_f (g/s)			0.179		0.191	

Table 11 Liquid-cooling TMS design results (HOV) - cruise condition

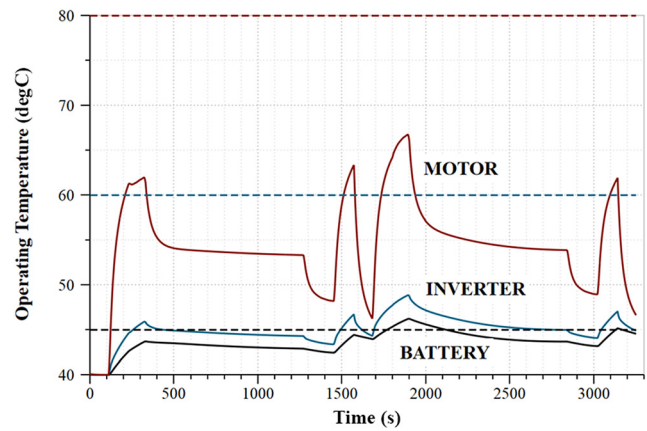
$W_{air, @OD}$ (kg/s)	3.19
$W_{coolant, @OD}$ (kg/s)	0.66
Total weight (kg)	76.45
Total power (kW)	101.98
Penalty in W_f (g/s)	0.720

drag power from the air duct is negligible when the aircraft is in a hovering state. The parallel configuration is reported to have a higher fuel burn penalty compared to the series configuration.

The changes in design parameters during the off-design condition (cruise) are outlined in Table 11. The extended operating duration necessitates a reduction in the battery operating temperature limit to 45 °C during the cruise condition. As a result, the initially designed air and coolant mass flow rates revealed insufficient cooling performance despite a substantial decrease in the heat load. Subsequently, both the air and coolant mass flowrate were increased, resulting in a 5.7-fold increase in the total power consumption of the designed TMS, encompassing the drag power induced by the air duct. The overall TMS penalty in fuel burn during the cruise phase also substantially increased, reaching more than twice that of the air-cooling TMS.

Figure 9 illustrates that the operating temperature profile of the electric powertrain components generally aligns with the requirements. Although the battery temperature slightly exceeds 45 °C during the second climb, as indicated by the dashed ellipse, it remains within the operating temperature requirement due to the duration being below 10 min (6.1 min). This increase is attributed to the rise in ram-air temperature during climb and descent.

Contrarily, the designed TMS seems to be overdesigned, given that the operating temperatures of the inverter and motor are notably

**Fig. 9 Operating temperature profile of the liquid-cooling TMS (HOV) – mission (dashed lines: limits)**

lower than the limit. This observation is clarified by examining the operating temperature profile during steady-state operation for both hover and cruise conditions, as depicted in Fig. 10. The solid and symbol lines represent the operating temperature profile during hover and cruise, respectively. The increase in air and coolant mass flow rates, despite lower thermal management requirements, results in overcooling of the inverter and motor. In the hover condition, a considerable amount of time is required to converge toward the designed operating temperatures, exceeding 1000 s. This prolonged duration is attributed to the thermal inertia present in the designed TMS.

4.2.2 Cruise—Design Point. Likewise, Table 12 displays the sizing results for liquid-cooling TMS designed at the cruise condition, encompassing both series and parallel configurations. Once more, the series configuration proves to be more effective than the parallel configuration. Based on the evaluations, it is determined that the series configuration is the preferable choice for the design of liquid-cooling TMS.

When assessing the off-design condition, regardless of the extent of the increase in air and coolant mass flow rates, the designed TMS proves inadequate to meet thermal management requirements at the hover condition. The challenge arises from the liquid-cooled cold plate design for the inverter and motor, where the heat load significantly surpasses the design point condition. In contrast, the liquid-cooled cold plate for the battery avoids this issue by having an increased battery operating temperature limit (57 °C). Consequently, two approaches are conducted to address this challenge:

A. Implementing PCMs as a heat storage system for the off-design condition

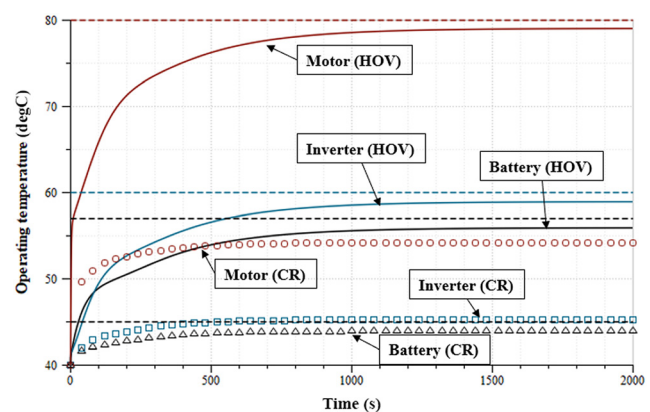
**Fig. 10 Operating temperature profile of the liquid-cooling TMS (HOV) – steady-state (dashed lines: limits)**

Table 12 Liquid-cooling TMS design results (CR) – cruise condition

Series			Parallel			
Cold plate						
	Battery	Inverter	Motor	Battery	Inverter	Motor
W_{coolant} (kg/s)		0.76		0.778	0.09	0.05
Weight (kg)	6.79	0.06	0.06	11.32	0.10	0.19
Width (m)	0.61	0.20	0.20	1.02	0.12	0.07
Length (m)	1.02	0.03	0.03	1.02	0.08	0.24
Auxiliary components						
	Pump	Puller fan	Air duct	Pump	Puller fan	Air duct
Weight (kg)	8.27	1.46	7.67	10.39	1.40	7.83
Power (kW)	0.009	12.05	20.79	0.009	11.84	19.83
Pressure ratio	—	1.04	—	—	1.04	—
Air-coolant heat exchanger						
ε_{HX}	W_{air} (kg/s)	Weight (kg)	ε_{HX}	W_{air} (kg/s)	Weight (kg)	
0.70	3.22	49.27	0.75	3.08		65.34
Width (m)	Length (m)	Height (m)	Width (m)	Length (m)	Height (m)	
2.49	0.13	0.10	2.65	0.16		0.10
Design summary						
			Series		Parallel	
Total weight (kg)			73.57		96.57	
Total power (kW)			32.80		31.69	
Penalty in W_f (g/s)			0.263		0.283	

B. Increasing the design heat load of the inverter and motor as the off-design condition

4.2.3 Approach A—Phase Change Materials as Heat Storage System. Table 13 presents the design results for the PCM heat storage system and the updated liquid-cooling TMS for the cruise condition. The overall TMS weight is nearly doubled, and the TMS penalty in fuel burn is increased by 24%.

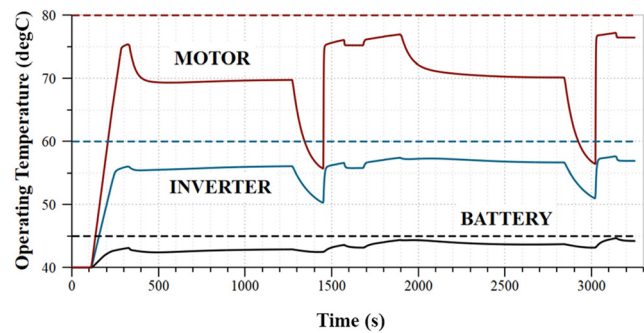
The operating temperature profile of the electric components aligns well with the requirements, as depicted in Fig. 11. Likewise, during the cruise condition, the motor and inverter experience overcooling due to the strict operating temperature limit of the battery. Also, the design of the liquid-cooled cold plate for the inverter and motor is converged to the minimum dimension constraints.

4.2.4 Approach B—Increased Design Heat Load. For Approach B, the TMS is redesigned to accommodate the elevated design heat load for the inverter and motor as the off-design condition. The corresponding design outcomes are detailed in Table 14, with only the series configuration evaluated. As a result, the designed TMS weight, power consumption, and fuel burn penalty all experience an increase.

Similarly, the designed TMS is evaluated for the off-design condition (hover), indicating the need to increase air and coolant

Table 13 Liquid-cooling TMS design results (CR-A)

	Battery	Inverter	Motor
Heat load (kJ)	9167.1	2817.1	5521.7
W_{PCM} (kg)	27.90	9.15	16.25
Total weight (kg)		126.87	
Total power (kW)		32.80	
Penalty in W_f (g/s)	0.325		

**Fig. 11 Operating temperature profile of the liquid-cooling TMS (CR-A) (dashed lines: limits)****Table 14 Liquid-cooling TMS design results (CR-B)**

Cold plate	Battery	Inverter	Motor
$W_{coolant}$ (kg/s)		0.88	
Weight (kg)	3.16	0.11	0.09
Width (m)	0.44	0.39	0.33
Length (m)	0.66	0.03	0.03
Auxiliary components			
	Pump	Puller fan	Air duct
Weight (kg)	9.85	2.13	9.24
Power (kW)	0.011	20.63	30.62
Pressure ratio	—	1.05	—
Air-coolant heat exchanger			
	ϵ_{HX}	W_{air} (kg/s)	Weight (kg)
	0.75	4.74	53.52
	Width (m)	Length (m)	Height (m)
	2.39	0.11	0.13
Total weight (kg)		78.11	
Total power (kW)		51.27	
Penalty in W_f (g/s)		0.382	

mass flow rates to comply with the operating temperature requirements.

Nevertheless, as evident from the operating temperature profile illustrated in Fig. 12, the operating temperature of the electric powertrain components remains well within the requirements even without increasing the air and coolant mass flow rates. This phenomenon can be attributed to the thermal inertia within the designed TMS and the relatively short duration of the off-design conditions. However, it is noteworthy that the motor and inverter components experience overcooling during cruise, as the

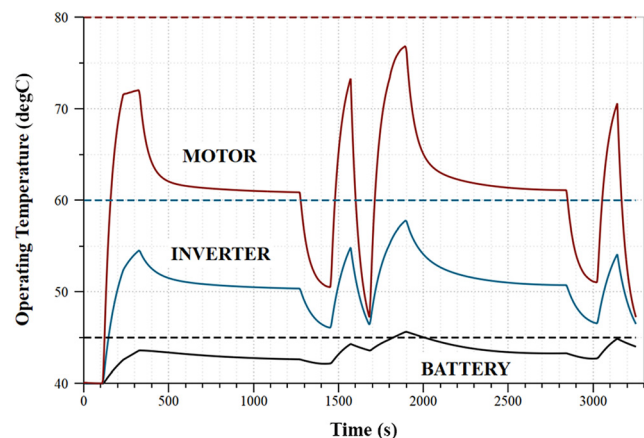
**Fig. 12 Operating temperature profile of the liquid-cooling TMS (CR-B) (dashed lines: limits)**

Table 15 Overall weight breakdown of the designed PHE aircraft

Weight breakdown (kg)	PHE – no TMS	PHE air	PHE liquid (HOV)	PHE liquid (CR-A)	PHE liquid (CR-B)
Aircraft structure [28]	1511.4	1511.4	1511.4	1511.4	1511.4
Fixed equipment group [28]	1017.4	1017.4	1017.4	1017.4	1017.4
Propulsion group	2526.0	2968.3	2791.4	2892.3	2794.7
Powerplant total	349.7	349.7	349.7	349.7	349.7
EPS	1103.6	1103.6	1103.6	1103.6	1103.6
TMS	—	442.2	265.4	366.2	268.7
Auxiliary system [28]	1072.7	1072.7	1072.7	1072.7	1072.7
Empty weight	5077.5	5519.7	5342.9	5443.7	5346.2
GTOW	6000.0	6000.0	6000.0	6000.0	6000.0
Fuel burnt	261.8	269.6	290.6	271.5	279.1
Payload available	660.7	210.7	366.5	284.8	374.7

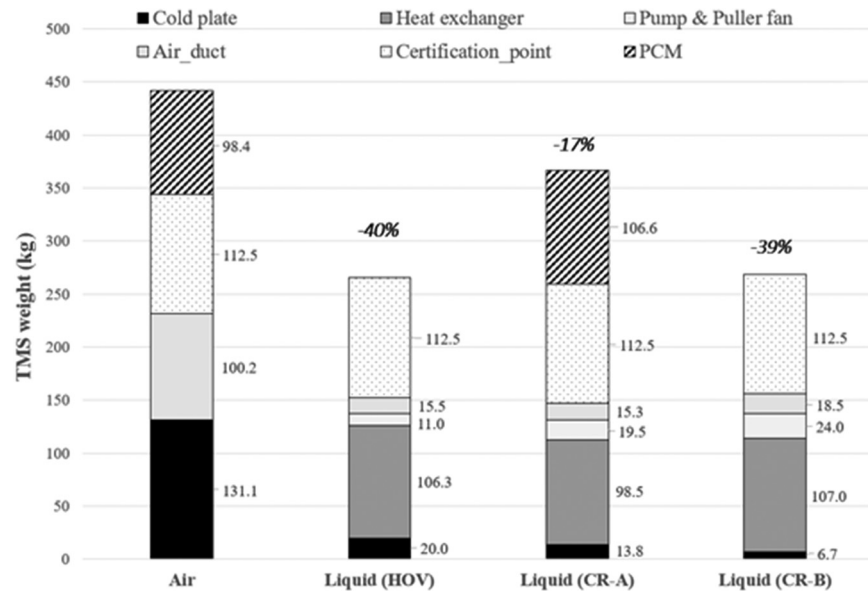


Fig. 13 Designed TMS weight comparison

liquid-cooled cold plates are designed based on the heat load at the hover condition.

4.3 Overall Performance Assessment. This section addresses the performance impact of the designed TMS on the PHE tiltrotor aircraft at the mission level. The weight breakdown of the XV-15 aircraft with the integrated TMS is determined based on TMS design and mission level assessment, as outlined in Table 15. Given the fixed GTOW for the mission, the available payload is varied according to the designed aircraft system and fuel burnt during the mission. Additionally, the weight breakdown of the PHE aircraft,

excluding the associated TMS penalty, is included to assess the impact of TMS integration on the aircraft. Note that the values represented in this section represent the configuration for two engines.

4.3.1 Impact on Payload. The designed TMS weights for the cases considered in the study are elaborated in Fig. 13. The incorporation of liquid coolant results in a significant decrease in cold plate weight, while the weight of additional components (air-coolant heat exchanger, pump, and puller fan) is added to the liquid-cooling TMS. Overall, the incorporation of liquid-cooling TMS results in a maximum of 40% weight reduction in the designed TMS.

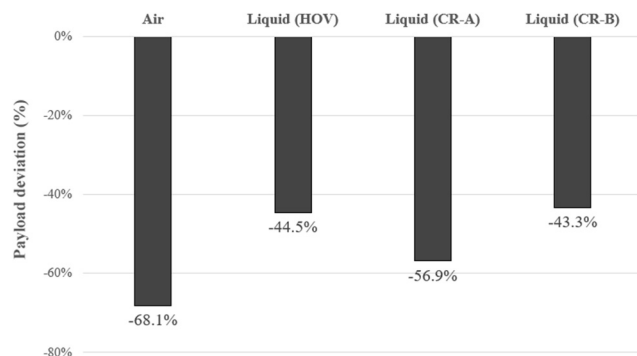


Fig. 14 TMS integration penalty on payload

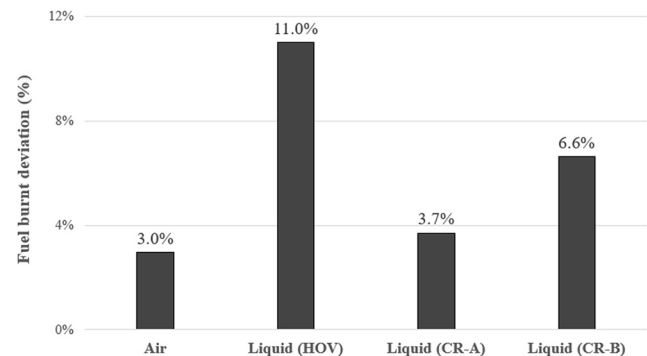


Fig. 15 TMS integration penalty on fuel consumption

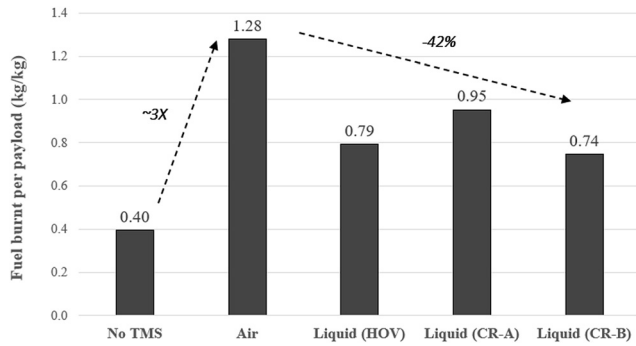


Fig. 16 Fuel consumption per payload

Subsequently, the payload deviation resulting from the TMS weight penalty is depicted in Fig. 14, showcasing a reduction of more than 40% in available payload due to the TMS weight penalty.

4.3.2 Impact on Fuel Consumption. Figure 15 illustrates the TMS integration penalty on fuel consumption. The designed liquid-cooling TMS shows a tendency for higher fuel consumption compared to the air-cooling TMS, attributed to the power offtake from the puller fan and coolant pump. Consequently, the highest fuel consumption increment of 11% is reported for the liquid-cooling TMS designed at hover condition, as the designed TMS operates mostly in its off-design condition during the operation.

4.3.3 Impact on Normalized Fuel Consumption. In Fig. 16, the normalized fuel consumption concerning the available payload is evaluated for the test cases considered in the study, providing insights into the fuel efficiency of the designed PHE tilt rotorcraft system. The TMS integration penalties, both in payload and fuel consumption, exert a significant impact on normalized fuel consumption, more than tripling when the air-cooling TMS is implemented. However, there is a notable 42% improvement in normalized fuel consumption when the liquid-cooling TMS, designed at cruise condition with Approach B (increased design heat load for inverter and motor as the hover condition), is employed.

5 Conclusion

This study explores the integration of a TMS into a PHE tiltrotor aircraft modeled after the NASA XV-15, assessing its resulting performance under specified conditions. The design mission comprising two consecutive 150-km range missions without any recharging in between is considered the sizing condition for the designed TMS. Both air and liquid-cooling TMS are designed to facilitate comparative analysis. The TMS required for OEI certification point condition is also considered by incorporating PCMs as a heat storage system.

The air-cooling TMS design incorporates a direct air-cooled cold plate for cooling and PCMs as a heat storage system. In contrast, the liquid-cooling TMS is designed to address high heat load conditions where the air-cooling TMS exhibited limitations. The liquid-cooling TMS comprises a liquid-cooled cold plate, an air-coolant heat exchanger, and additional auxiliary components. Both TMS are designed with a comprehensive approach aimed at minimizing penalties associated with weight and power consumption of the designed TMS.

Two liquid-cooled cold plate configurations, series and parallel, are assessed, with the series configuration proving more efficient for the considered test cases. Two design point conditions are also explored for the liquid-cooling TMS to identify the optimal design point: Hover (peak heat load condition) and Cruise (nominal heat load condition).

Designing for the hover condition results in significant overcooling of electric powertrain components due to the short duration of the design condition. Thermal inertia in the TMS leads to a

prolonged time (more than 1000 s) to reach designed operating temperatures. Additionally, power consumption sees a substantial increase during the off-design condition (cruise), resulting in about a fourfold increase in the overall TMS penalty in fuel burn during cruise.

Conversely, designing the liquid-cooling TMS for the cruise condition proves infeasible to comply with the thermal management requirements during the off-design condition (hover). Two approaches are conducted: Approach A involves adding PCMs as a heat storage system, and Approach B entails redesigning the TMS with the heat load at off-design conditions for the inverter and motor. Both approaches led to an increase in the overall TMS penalty in fuel burn compared to the design that solely considered cruise condition, by 24% and 45%, respectively.

Subsequently, the designed PHE tiltrotor aircraft systems, with an integrated TMS for the considered test cases, are assessed at the mission level. The liquid-cooling TMS designed at cruise condition with Approach B emerges as the optimal TMS design, exhibiting a 42% improvement in fuel burnt per payload compared to the air-cooling TMS.

As a future work, establishing a multidisciplinary optimization platform aimed at evaluating the impact of TMS design during the early design phase is suggested. This recommendation stems from the fixed GTOW of the aircraft in the current study, with the understanding that performance results may vary when the maximum takeoff weight of the aircraft is considered. Furthermore, the PMS should be optimized, taking into account the impact of the TMS.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

Nomenclature

ε	= effectiveness
ρ	= density (kg/m^3)
A	= area (m^2)
c_p	= specific heat capacity ($\text{kJ/kg}\cdot\text{K}$)
DOH	= degree of hybridization
GTOW	= gross take-off weight (kg)
HEPS	= hybrid electric propulsion system
ISA	= International Standard Atmosphere
K_{spill}	= empirical spillage coefficient
LHF	= latent heat of fusion (kJ/kg)
m	= mass (kg)
NLPQL	= nonlinear programming quadratic line search
OD	= off design
OEI	= one engine inoperative
P	= power (kW)
PCM	= phase change material
PMS	= power management strategy
SOC	= state of charge
T	= temperature ($^{\circ}\text{C}$)
TMS	= thermal management system
UAM	= urban air mobility
v	= velocity (m/s)
VTOL	= vertical take-off and landing
W	= mass flow rate (kg/s)

Subscripts

f	= fuel
GT	= gas turbine
HX	= heat exchanger
OD	= off-design

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Design and simulation of eVTOL aircraft Thermal Management System

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