

Design and Simulation of an Enhanced Cooling Structure for Electro-Hydrostatic Actuator Motor in Hypersonic Aircraft

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Keywords : electro-hydrostatic actuator, enhanced cooling structure, motor heat generation, computational fluid dynamics.

cooling structure significantly improves heat dissipation uniformity and the thermal safety margin for actuator systems in hypersonic aircraft.

ABSTRACT

Thermal management is a key barrier to the safe operation of electro-hydrostatic actuators in hypersonic aircraft, where severe aerodynamic heating and time-varying actuation loads can drive permanent-magnet motor temperatures toward critical limits. To address excessive temperature rise, this paper proposes a novel integrated axial Z-shaped liquid cooling channel for the electro-hydrostatic actuator motor housing to enhance heat dissipation performance. A comprehensive mathematical model is established, and computational fluid dynamics simulations are employed to evaluate the thermal-hydraulic characteristics of the design. Comparative simulations were conducted under two typical flight conditions and a full mission profile to benchmark the Z-shaped channel against the original coil-shaped channel. The results demonstrate that under the attitude adjustment condition, the Z-shaped channel reduces the average housing, stator and winding temperatures by 4.1%, 9.2% and 8.6%, compared with the coil-shaped channel. Under the peak-load condition, the corresponding reductions are 3.6%, 10.9% and 4.6%. Transient simulations over the full flight profile indicate that all component temperatures remain strictly below the 135°C safety limit, with the maximum housing temperature maintained at 128°C. These findings confirm that the proposed Z-shaped

INTRODUCTION

In hypersonic aircraft, electric actuation is increasingly used to replace traditional hydraulic actuation for improved weight and maintainability. Among these solutions, electro-hydrostatic actuator (EHA) is the representative power-by-wire architecture for flight-control surfaces (Naayagi, 2013). Compared with conventional actuators, the EHA is an electrically driven device that reduce reliance on large-scale hydraulic piping systems and external hydraulic sources (Li et al., 2016). Specifically, an EHA integrates a local motor-pump unit so that hydraulic power can be generated on demand by regulating pump speed, consistent with the power-by-wire concept (Xiao et al., 2024). This architecture can simplify hydraulic routing and potentially reduce system weight and maintenance requirements (Karttunen et al., 2014). These advantages in weight reduction and system simplification are particularly critical for hypersonic aircraft, which demand exceptionally high levels of reliability and maneuverability.

However, thermal management remains a key barrier to reliable operation of EHA motors in hypersonic environments. This paper designs a compact Z-shaped liquid-cooling channel for an EHA motor and evaluates its performance through comparative CFD simulations under representative hypersonic operating conditions. During actuation of control surfaces, the permanent magnet motor, a core component of the EHA, generates substantial heat losses (Xu et al., 2014). As noted in the research of (Du et al., 2020), NdFeB magnets may experience demagnetization when their temperature exceeds 150–200°C, and elevated temperatures also accelerate insulation material degradation (Chen et al., 2024a). Furthermore, the full-flight of hypersonic aircraft induces severe aerodynamic heating, particularly

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during ascent and atmospheric reentry, exposing the system to extreme thermal loads(Huang et al., 2024a). The ambient temperature in EHA installation zones can reach 135°C or higher(Gao et al., 2025). These elevated temperatures can further degrade the performance of adjacent components, thereby indirectly increasing the thermal load on the EHA.(He et al., 2025). Moreover, passive cooling methods are insufficient to dissipate both the internal heat losses and the external heat simultaneously(Li et al., 2025).

Numerous studies have investigated liquid-cooling channel designs for permanent-magnet motors to improve heat removal and temperature uniformity. In terms of structural design for permanent magnet motor cooling, (Chen et al., 2024a) proposed a liquid-cooling structure incorporating parallel straight channels, parallel curved channels, and series curved channels within one motor housing. (Fan et al., 2020) embedded water-cooling plates inside the housing, shortening the heat transfer path. (Chen et al., 2024b) developed a dual-helix hybrid axial Z-type water channel for underwater motors, which enables internal circulation cooling without an external reservoir. (Huang et al., 2024b) systematically compared helical, circumferential Z-type, and axial Z-type channels, concluding that the helical channel offers the most favorable flow uniformity and pressure drop, while the Z-type channel achieves a good balance between cooling efficiency and flow resistance. (Zhang and Ge, 2022, Luo et al., 2021) proposed a miniaturized, integrated axial U-type cooling structure embedded within the housing of automotive motors, which can serve as a reference for compact EHA cooling system designs. Furthermore, precise mathematical modeling can be employed to optimize the cooling system. (Zhang et al., 2024) thermal-resistance modeling and heat-transfer correlations can guide preliminary sizing of channel geometry and flow rate, noting that the marginal benefit of increasing flow may diminish beyond a critical Reynolds number. For hypersonic applications, both aerodynamic heating and time-varying power loss should be considered, which motivates mission-profile-based thermal evaluation of EHA motors under realistic environmental boundary conditions (Huang et al., 2024a, He et al., 2025, Du et al., 2020). (Chang and Weng, 2022) use CFD methods to predict the thermal-flow fields and characteristics over a spherically blunted tangent-ogive nose cone at 6 Mach. Provides useful data for hypersonic flight, especially the heat distribution of temperature. These approaches can also be effectively applied to EHA thermal simulations. (Tang et al., 2023)investigated the simulation methods for motor temperature fields under variable loads, providing a valuable reference for the transient cooling simulation requirements of EHAs in hypersonic aircraft.

This paper proposes a novel active cooling structure for the EHA motor used in a hypersonic aircraft. First, the EHA motor heat generation and

thermal loads are quantified by establishing a mathematical model and defining the corresponding thermal boundary conditions. Second, a Z-shaped active cooling structure is designed, which is incorporated into the aircraft's cooling circuit to achieve dual functions of ambient heat isolation and internal heat absorption. Third, the cooling performance is evaluated under representative hypersonic flight conditions, with comparative CFD simulations carried out against the original channel and the novel channel. Finally, the Z-shaped channel was selected for full flight profile simulation to evaluate its effectiveness.

MODELING OF COOLING STRUCTURE

Physical Model of the EHA Motor

In this paper, the research object is the motor section of a rudder EHA used in hypersonic aircraft. The EHA permanent magnet motor model, as shown in Fig.1, primarily consists of the housing, stator, windings, rotor, end caps, and an external liquid-cooling channel integrated on the housing.

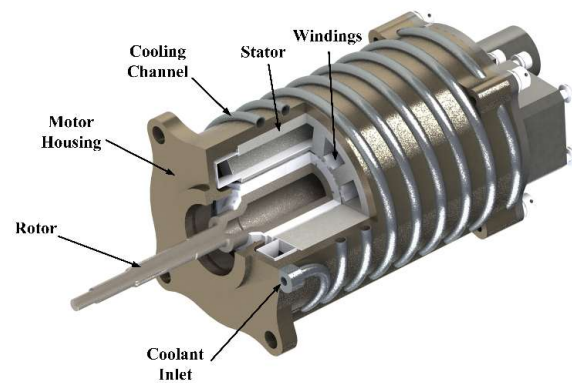


Fig. 1 Physical structure of the EHA motor.

The investigated EHA adopts an oil-immersed motor–pump configuration. The leakage hydraulic oil from the pump is routed into the motor cavity and circulates through the interior, which enhances internal convection and facilitates heat transfer from the rotor region to the housing. Meanwhile, an external liquid-cooling channel is integrated on the outer surface of the housing. A 40/60 ethylene-glycol/water mixture is used as the coolant in the external channel to remove heat from the housing.

This permanent magnet motor has a total length of 193.5 mm, with the housing section length of 105.2 mm. The motor employs a 6-pole/9-slot concentrated winding, and its key specifications are summarized in Table 1. The thermal properties of the main motor components are listed in Table 2.

Table 1 Key parameters of the motor

Motor Parameter	Value
Maximum rotational speed n_s	10500 rpm
EHA actuator efficiency η_w	60 %

EHA motor efficiency η_m	82 %
Housing outer diameter D_h	62 mm
Maximum cooling channel outer diameter D_m	72 mm
Maximum cooling channel axial length L_m	92 mm

Table 2 Material parameters of EHA motor

Part	Rotor	Stator	Winding	Housing
Material	Cobalt alloy	Silicon steel	Copper	Aluminum
Density kg/m^3	8400	7650	8960	2700
Thermal conductivity $\text{W/(m} \cdot \text{K)}$	16	26	385	237
Specific heat capacity $\text{J/(g} \cdot \text{K)}$	0.42	0.46	0.39	0.9

Heat Generation Modeling and Loss allocation

The thermal input in this paper is derived from the measured power-spectrum data of a representative rudder EHA obtained from a system-level experiment, which provides the actuator output power as a function of time under a typical mission profile. The output power of the rudder EHA is P_a .

To convert the experimental power spectrum into the motor thermal input, the power deficit associated with the motor efficiency is defined as the motor heat generation.

$$Q_t = \frac{P_a}{\eta_m} (1 - \eta_m) \quad (1)$$

where Q_t is motor heat generation rate.

Under the full flight profile, the ambient temperature T_e is higher than the motor housing temperature and the coolant temperature in some conditions. Therefore, heat is transferred from the ambient into the motor system, forming an external thermal load. Consequently, the external liquid-cooling channel serves not only to remove the internally generated heat Q_t but also to intercept ambient heat Q_e intrusion. Thus, the total heat load input to the motor model is Q_m .

$$Q_m = Q_t + Q_e \quad (2)$$

The loss distribution coefficients a_j are determined based on the internal loss mechanisms of the motor. According to the data obtained from the experiment, the loss-allocation to each component of the rudder EHA motor are shown in Table 3. Loss allocated to each component is therefore given by:

$$Q_j = a_j Q_m \quad (3)$$

Table 3 Loss-allocation factors for the EHA motor

Component	Winding	Stator	Rotor	Housing
Symbol	a_w	a_s	a_r	a_h
Allocation factor a_j	0.45	0.3	0.15	0.10

Thermal Node Modeling

Assume that the coolant in the cooling channel flows unidirectionally and absorbs heat. The gradient of the mean fluid temperature with respect to position

$s \in [0, L]$ along the channel can be expressed as

$$\dot{m} c_p \frac{dT_f}{ds} = q'(s) \quad (4)$$

where $\dot{m}$ is the mass flow rate of the fluid. c_p is specific heat capacity of the fluid. $q'(s)$ is the rate of heat transfer into the coolant per unit length of the channel at location.

Integrating from the inlet to a local position the local bulk fluid temperature $T_f(s)$:

$$T_f(s) = T_{in} + \frac{1}{\dot{m} c_p} \int_0^s q'(s) ds \quad (5)$$

where T_{in} is the coolant inlet temperature.

The local convective heat transfer is described as:

$$q'(s) = h(s) \cdot P \cdot [T_w(s) - T_f(s)] \quad (6)$$

where P is the wetted perimeter and $h(s)$ is the local heat transfer coefficient.

The wall temperature is:

$$T_w(s) = T_f(s) + \frac{q'(s)}{h(s)P} \quad (7)$$

The heat generated in the windings must conduct through a composite solid structure to reach the coolant. This path typically includes the insulation layer, the stator core, and the housing. These layers are treated as a series of thermal resistances. The equivalent conductive thermal resistance R_c is defined as the sum of the resistances of these solid components.

$$R_c = R_i + R_s + R_h \quad (8)$$

Thus, the relationship between the winding temperature and the channel wall temperature is:

$$T_s(s) = T_w(s) + q'(s) R_c \quad (9)$$

$$T_s(s) = \left[T_{in} + \frac{1}{\dot{m} c_p} \int_0^s q' ds \right] + q'(s) \left[\frac{1}{h(s)P} + R_c \right] \quad (10)$$

Since R_c is fixed by materials, the only variable is the local convective heat transfer coefficient $h(s)$.

the local heat transfer coefficient $h(s)$ is analyzed via the Nusselt number, defined as:

$$h(s) = Nu(s) \frac{k_f}{D_c} \quad (11)$$

where D_c is the channel diameter, k_f is thermal conductivity of coolant.

Convective Coefficient Modeling

In this rudder EHA motor, the original cooling structure is a coil-shaped channel, spirally arranged along the housing axis. In this structure, heat transfer augmentation is primarily driven by centrifugal instability-induced secondary flows, referred to as Dean vortices. These vortices promote fluid mixing and disrupt the thermal boundary layer continuously

along the curved sections. The Nusselt number distribution is modeled as a continuous function of the Dean number De is defined as:

$$De = Re \sqrt{\frac{D_h}{2R_c}} \quad (12)$$

Define Nu_0 as the baseline Nusselt number for a hydraulically equivalent straight channel under the same flow conditions.

$$Nu_c(s) = Nu_0 \cdot [1 + 0.18(De)] \quad (13)$$

Therefore, a deterministic Nusselt number can be established via numerical computation. To maximize heat dissipation within identical installation envelopes, the primary objective is to elevate the Nusselt number. This paper designs a novel axial Z-shaped cooling channel. By introducing multiple bends, the proposed design achieves a convective heat transfer coefficient significantly higher than that of the coil-shaped configuration, while maintaining a nearly equivalent effective heat transfer area.

The streamwise Nusselt number distribution for the Z-shaped channel, $Nu_z(s)$, is modeled as a baseline value superimposed with a series of decaying enhancement pulses triggered by the bends:

$$Nu_z(s) = Nu_0 \cdot \left[1 + \sum_{i=1}^{N_b} A_b \cdot e^{\left(-\frac{s-s_i}{L_b}\right)} \cdot H(s-s_i) \right] \quad (14)$$

where N_b is the total number of bends in the channel. A_b is the peak Nusselt number amplitude ratio. L_b is thermal decay length. $H(s-s_i)$ is Heaviside step function.

The Z-shaped channel functions as a periodic boundary layer disruptor. By maintaining the bend pitch below the thermal decay length L_b , the design forces a reset of the thermal boundary layer before it fully redevelops. This mechanism eliminates low heat transfer regions typical of developed flows, effectively mitigating local hotspots and enhancing temperature uniformity.

Hydraulic Performance Model

Heat transfer incurs the total pressure drop Δp across the channel consists of major frictional losses and local minor losses, Z-shaped channel can expressed as:

$$\Delta p = \frac{1}{2} \rho u^2 \left(f \frac{L}{D_h} + \sum K_j \right) \quad (15)$$

where u is mean flow velocity. f is Darcy friction factor. K_j is local loss coefficient.

To quantify the heat dissipation performance of the cooling system, the pump power P_p is defined as:

$$P_p = \Delta p \cdot \dot{V} = \Delta p \cdot \frac{\dot{m}}{\rho} \quad (16)$$

where $\dot{V}$ is volumetric flow rate.

In this paper coolant operates in an independent

circulation loop, the validation is conducted under an identical constant flow-rate. By fixing the inlet coolant flow rate, the present comparison isolates the heat-transfer enhancement attributable to the channel geometry, rather than mixing geometric effects with flow-rate variations. Simulations are employed to compare the coolant outlet temperature and peak heat source temperature of the Z-shaped channel with Coil-shaped channel, thereby verifying the superior heat dissipation performance of the proposed design.

COOLING STRUCTURE DESIGN

Heat generated in the EHA motor is difficult to remove through the internal cavity alone, which can lead to localized high-temperature regions near the rotor and end-winding areas. Since the heat sources of the EHA system include both the permanent-magnet motor and the plunger pump, the cooling structure must be kept as simple as possible to minimize system weight and complexity. Therefore, the hydraulic oil leaked from the plunger pump is directed into the motor, transforming it into the oil-immersed motor-pump EHA.

With hydraulic oil flowing through the motor interior, the heat from high-temperature region can be transferred more effectively to the housing. The hydraulic oil not only removes heat generated by the plunger pump but also enhances internal heat transfer within the motor. The oil inlet and outlet are located at the two end caps of the motor. In this configuration, the hydraulic oil and the external cooling structure on the motor housing together form a localized heat-exchange system. The heat loads from both the motor and the plunger pump are ultimately dissipated by the coolant flowing through the cooling structure.

The coil-shaped cooling structure is the original designed structure. In certain situations, this structure exhibits uneven heat dissipation in some regions, resulting in insufficient cooling performance. Thus the designed Z-shaped channel is proposed as the enhanced cooling structure for EHA motors.

Coil-shaped Channel

The original EHA design adopts a circumferential flow cooling structure. The coolant enters through the inlet, spirals around the motor circumference, and finally exits through the outlet. The key structure parameters of coil-shaped channel as shown in Table 3.

Table 3 Coil-shaped channel key structure parameters

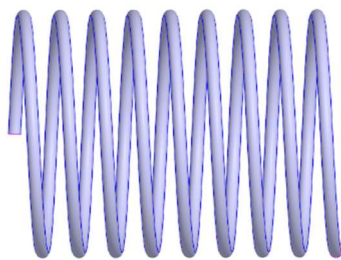
Key parameter	Value
Outer diameter D_{co}	4mm
Inner diameter D_{ci}	3mm
Flow path length L_{fp}	1761mm
Heat exchange area A_{CH}	0.0178243 m ²

Both the internal heat generation and the external ambient heat intrusion are ultimately removed

by the coolant flowing through the coil-shaped channel. Fig. 2 shows the structure of the coil-shaped channel. The coolant supplied by the thermal-management system flows through an independent circulation loop to provide active coolant for the motor.



a. Structure of Coil-shaped channel



b. The fluid domain of a coil-shaped channel

Fig. 2 Coil-shaped channel

Z-shaped Channel

To overcome the laminar flow limitations, a novel axial Z-shaped channel is proposed. By forcing the coolant to travel axially and reverse direction sharply at the end caps, the design functions as a periodic boundary layer disruptor to induce strong turbulence. In the axial Z-shaped channel, the coolant travels along the axial direction of the motor and changes direction at each bend, forming a continuous circulation path before exiting through the outlet of the cooling structure.

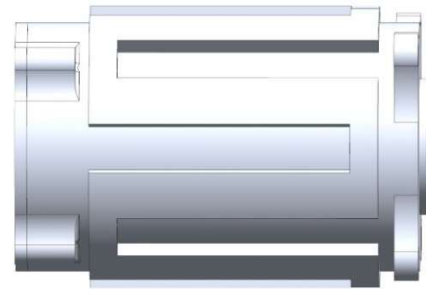
Increasing the number of bends enhances the turbulence of the coolant flow, but also leads to higher pressure losses. Considering a reasonable pressure drop and the relevant installation constraints, the key structural parameters of the Z-shaped channel are determined through mathematical modeling and optimization, as summarized in Table 4.

Table 4 Z-shaped channel key structure parameters

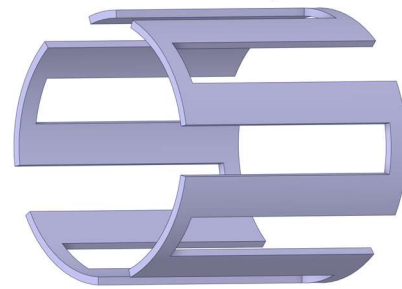
Key parameter	Value
Pipe length L_{zp}	72mm
Pipe inner diameter R_{id}	2mm
Pipe width W_{zp}	12.16mm
Pipes gap W_g	10.77mm
Channel length L_z	720.16mm
Bend number	36
Heat exchange area A_{ZH}	0.0171354m ²

To enable a fair comparison with the original coil-shaped cooling structure, the Z-shaped heat

exchange area with the motor is 0.0171354m², which is deliberately designed to be approximately equal to that of the coil-shaped structure. Shown as Fig. 3.



a. Structure of Z-shaped channel



b. The fluid domain of a Z-shaped channel

Fig. 3 Z-shaped channel

SIMULATION AND ANALYSIS

Numerical Method and Validation

The three-dimensional conjugate heat transfer (CHT) and fluid flow simulations were performed using the commercial CFD code ANSYS Fluent. To accurately capture the complex flow separation and reattachment induced by the sharp bends in the Z-shaped channel, the Realizable $k-\varepsilon$ turbulence model with enhanced wall treatment was adopted. To resolve the viscous sublayer near the walls, the first layer height of the boundary layer mesh was refined to ensure the dimensionless wall distance $y^+ \approx 1$. The pressure-velocity coupling was handled using the coupled algorithm. Second-order upwind schemes were employed for the spatial discretization of momentum and energy equations to ensure numerical accuracy. The convergence criteria were set to 10^{-6} for the energy equation and 10^{-4} for continuity and momentum equations. For the full flight profile simulation, a transient solver was utilized with a fixed time step of 1.0 s to capture the time-varying thermal response.

To eliminate the influence of mesh density on the simulation results, a grid independence test was conducted. Three distinct mesh systems with cell counts of approximately 1.2 million, 2.5 million, and 4.8 million were evaluated under the rated working condition. The comparison revealed that the relative deviation in the average housing temperature between the 2.5 million and 4.8 million grids was less than 1%.

Consequently, the mesh system with 2.5 million cells was selected for all subsequent simulations.

Boundary Conditions and Case Descriptions

To evaluate the thermal performance of Z-shaped cooling structure for the EHA motor. CFD simulations are conducted under several typical conditions corresponding to the flight profile. Choose the natural convection condition as the baseline case. And two typical scenarios are selected: the attitude-adjustment condition during in-flight maneuvering (Condition C.1) and the peak-load condition triggered during emergency operations (Condition C.2).

The motor heat losses are calculated using the thermal load model, and the total heat loss is distributed among the housing, stator, windings, and rotor according to the corresponding loss mechanisms. The heat-loss power is set to 120W in Condition C.1 and 160W in Condition C.2.

The designed external cooling channel uses a 40/60 ethylene-glycol/water as the coolant. Depending on the thermal control requirements, the coolant inlet temperature and flow rate can be adjusted. For the two conditions, the coolant inlet temperature is set to 80 °C. And the coolant flow rate is specified as 5 L/min for condition C.1 and 3.5 L/min for condition C.2. The ambient temperature surrounding the actuator is set to 135 °C for simulations. And a natural-convection condition(N.C) without external cooling methods is set as the baseline for simulation.

The boundary conditions for the three simulation cases are summarized in Table 5.

Table 5 The boundary conditions of simulations

Conditions	N.C	C.1	C.2
Heat-loss power	120W	120W	160W
Coolant inlet temperature	None	80°C	80°C
Coolant flow rate	None	5L/min	3.5L/min
Hydraulic-oil inlet temperature	105°C	105°C	90°C
Ambient temperature	135°C	135°C	135°C

Natural Convection Simulation and Analysis

The natural convection condition is the baseline for simulations. In this condition, no external active cooling flow is applied, and heat dissipation relies on natural convection between the motor housing and the surrounding air, as well as the internal hydraulic oil circulation within the motor. The ambient thermal load is also conducted into the motor. Based on the boundary conditions listed in Table 5, the heat-loss power is set as 120W. No external coolant. And ambient temperature is 135°C, the inlet temperature of the hydraulic oil is 105°C. The simulation results for the natural convection case are shown in Fig. 4.

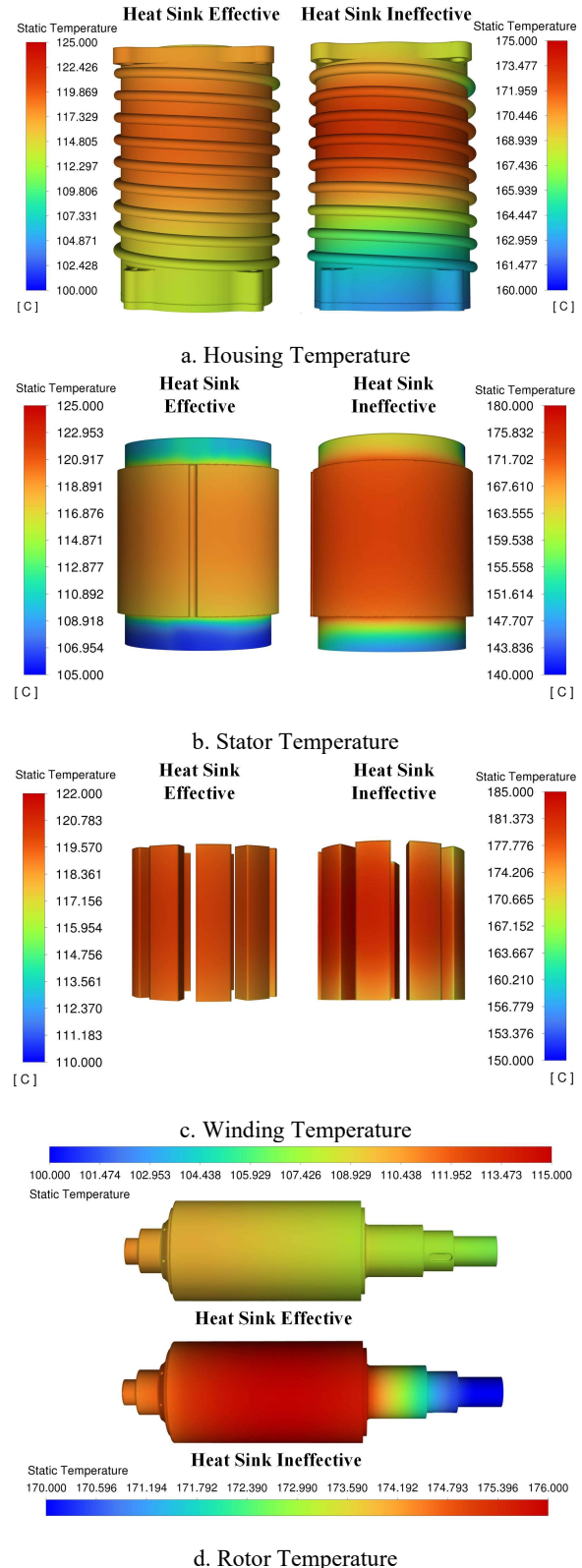


Fig. 4 Natural Cooling Simulation Results
As illustrated in Fig. 4, under the high ambient temperature of 135°C, the passive cooling capacity is severely insufficient. Even with the internal hydraulic oil circulation acting as a partial heat sink, the average housing temperature stabilizes at approximately 119.2°C, while the winding temperature reaches a

critical level of 122.8°C. More critically, as the hydraulic oil temperature rises to match the motor components approaching 117°C, its capacity to absorb heat diminishes. If the internal heat sink fails, the thermal runaway becomes evident, the maximum winding temperature surges to 181°C, and the permanent magnets reach 176°C. These temperatures exceed the demagnetization threshold of NdFeB magnets, posing a catastrophic risk to the aircraft's safety.

These results quantitatively confirm that passive cooling strategies are inadequate for hypersonic applications, necessitating the implementation of the proposed active liquid-cooling structures.

Attitude Adjustment Condition Simulation and Analysis

For the attitude-adjustment condition during in-flight maneuvering, the EHA motor is actively cooled using a 40/60 ethylene-glycol/water. The coolant inlet temperature is set to 80 °C, and the flow rate is specified as 5 L/min. Hydraulic oil circulates inside the wet-rotor motor, enhancing heat transfer from the rotor to the housing. The combined effect of internal oil circulation and the external cooling channel promotes efficient heat removal. The heat generation of the motor in this condition is 120 W.

All boundary conditions are set to be the same. The simulations are carried out separately for coil-shaped channel and Z-shaped channel to allow a direct comparison of their thermal performance. Fig. 5 presents the simulation results for the coil-shaped channel and Z-shaped channel under the motor heat-loss power of 120W.

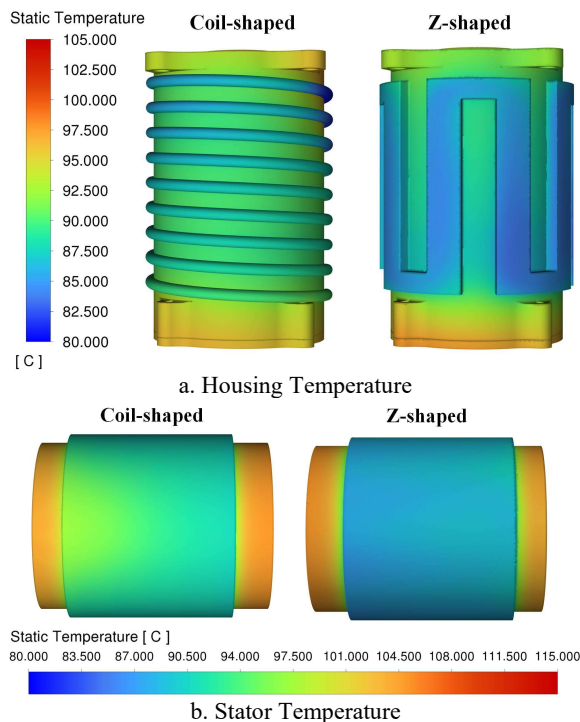
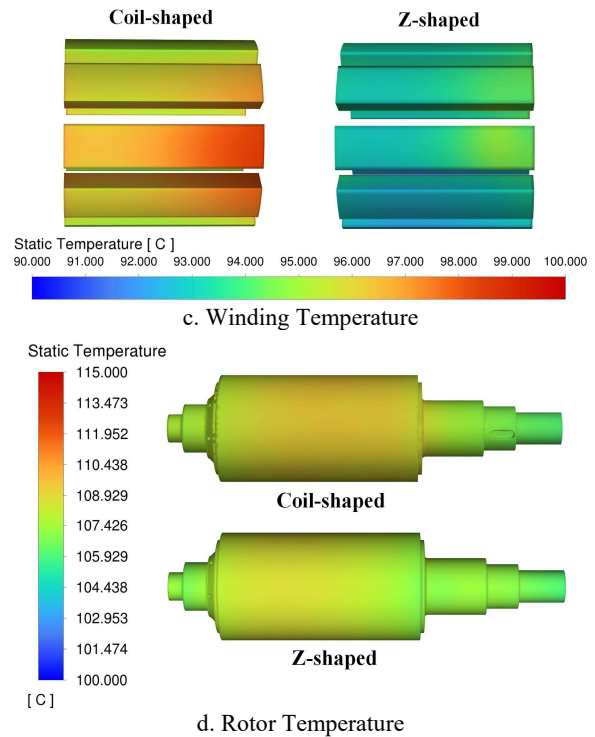


Fig. 5 The Result of Attitude Adjustment Condition

Under the C.1 condition, all component temperatures of the motor with cooling channel show a significant reduction compared with the natural convection condition.

Table 6 Results under Condition C.1

Conditions	Coil-shaped	Z-shaped	Improvement
Avg. Housing Temperature	92.7 °C	88.9 °C	-4.10%
Avg. Stator Temperature	95.3 °C	86.5 °C	-9.20%
Avg. Winding Temperature	95.9 °C	87.5 °C	-8.60%
Pressure Drop	371120 Pa	660695 Pa	
Pumping Power	31 W	55 W	+78.0%

As detailed in Table 6, Compared with the coil-shaped channel, the Z-shaped channel demonstrates a significantly improved thermal performance. The average motor temperature with the Z-shaped channel is 88.9 °C, which is 4.1% lower than the coil-shaped channel. The stator core reaches an average temperature of 86.5 °C, 8.6% lower than that in the coil-shaped channel, indicating a more uniform heat distribution in the stator region. The winding temperature under the Z-shaped channel is approximately 87.5 °C, which is 8.2 °C lower than that of the coil-shaped channel. For the rotor, since the hydraulic oil flows through the central cavity and removes part of the heat, the temperatures of the two cooling structures are relatively close. The coolant outlet temperature is around 87.8 °C, while the hydraulic oil outlet reaches 104.3 °C, indicating that a significant portion of the motor's thermal load is effectively removed.

Compared with the Coil-shaped structure, every component of the Z-shaped structure motor has a

significantly lower average temperature than the Coil-shaped motor in the attitude adjustment Condition. Under the same boundary conditions, the Z-shaped channel motor demonstrates better cooling performance.

Result of Peak Load Condition Simulation and Analysis

To assess the thermal performance of the cooling structures under extreme conditions, simulations were conducted for the peak-load condition, denoted as the Condition C.2. In this case, the motor experiences a heat generation power of 160W, while the coolant inlet temperature is set to 80 °C with a reduced coolant flow rate of 3.5 L/min. The hydraulic oil inlet temperature is 90 °C, and the external ambient temperature surrounding the actuator is 135 °C. All other boundary conditions remain consistent with previous simulations.

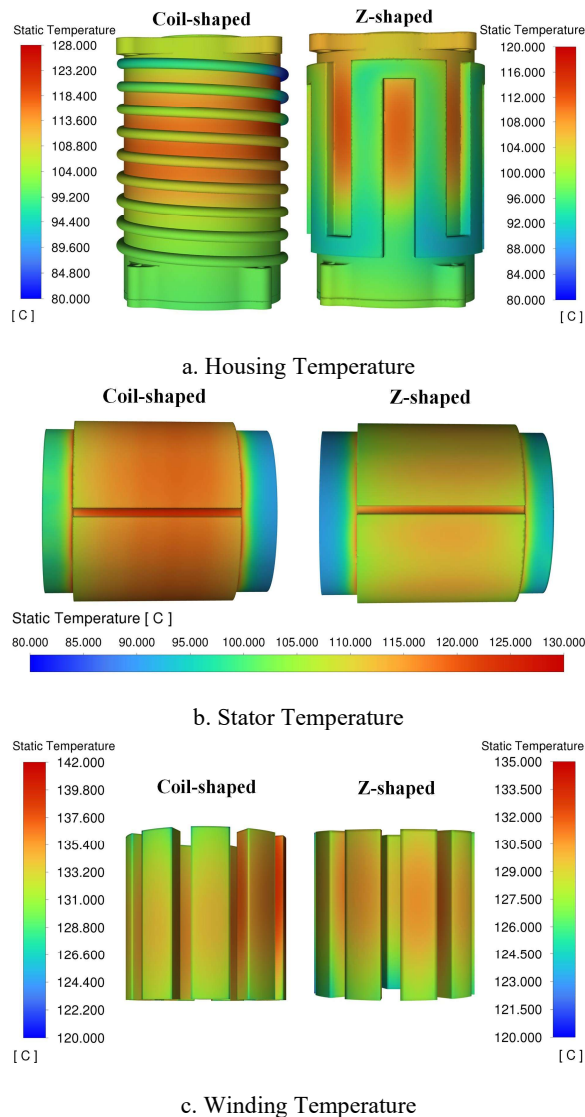
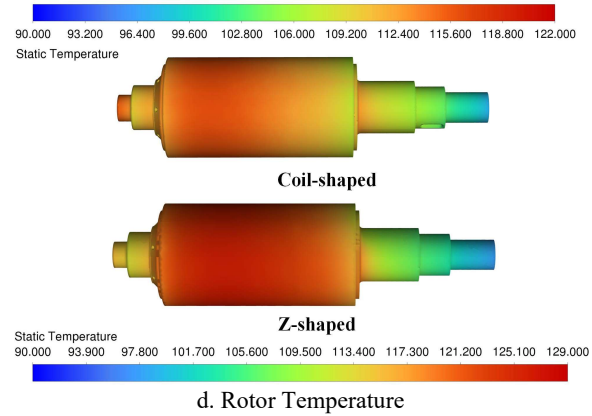


Fig. 6 The Result of Peak Load Condition

As shown in Fig. 6, the motor temperatures rise significantly compared with the attitude-adjustment condition (C.1). The stator and winding temperatures of coil-shaped structure reach critical levels, and local hot spots appear in the winding region, indicating uneven heat dissipation. The rotor temperature is moderately controlled due to hydraulic oil circulation, the cooling efficiency of the coil-shaped channel is limited under high heat flux.

Table 7 Results under Condition C.2

Conditions	Coil-shaped	Z-shaped	Improvement
Avg. Housing Temperature	113.1 °C	109 °C	-3.60%
Avg. Stator Temperature	123.5 °C	110 °C	-10.90%
Avg. Winding Temperature	135.1 °C	128.8 °C	-4.6%
Pressure Drop	194,540 Pa	346,310 Pa	
Pumping Power	11.6	20.6	+77.5%

Table 7 represents the thermal limit during emergency flight maneuvers. In this scenario, the coil-shaped channel fails to provide uniform cooling, leading to localized hotspots in the winding region. Conversely, the Z-shaped channel maintains excellent temperature uniformity. the Z-shaped design reduces the average housing temperature by 4.1°C and the stator temperature by 13.5°C compared to the baseline. Most notably, it maintains the winding temperature at a safe level of 128.8°C without any local hotspots, whereas the coil-shaped design shows dangerously uneven dissipation. Although the Z-shaped channel requires a higher pressure drop to sustain the required flow, this trade-off is essential to prevent permanent magnet demagnetization during peak-load phases

These results confirm that the Z-shaped channel not only improves cooling performance under normal conditions but also ensures better thermal management during peak-load events, making it a robust solution for maintaining the safety of EHA.

While the Z-shaped channel significantly improves thermal performance, it is crucial to evaluate the associated hydraulic costs. As detailed in Table 6 and Table 7, the complex bend of the Z-shaped channel results in a higher pressure drop compared to the coil-shaped channel. Specifically, under the

attitude-adjustment condition, the pumping power requirement increases by 78.0% from 31 W to 55 W; similarly, under the peak-load condition, it increases by 77.5% from 11.6 W to 20.6 W. Although the relative percentage increase appears substantial, the absolute increase in power consumption is still acceptable and valuable.

Thus, it can be concluded that, whether C.1 and C.2, the Z-shaped channel motor has better heat dissipation performance compared to the Coil-shaped motor. Therefore, adopting the Z-shaped channel as the cooling structure for the EHA motor is the most reasonable choice.

Full Flight Profile Simulation and Analysis

The steady-state simulations have already demonstrated that the Z-shaped channel outperforms the coil-shaped channel in terms of heat dissipation. To further evaluate the effectiveness of the Z-shaped channel during an actual flight, a full flight profile simulations are conducted to track the actuator's temperature as the heat loss power, coolant inlet temperature, and ambient temperature vary throughout the flight. The flight profile is divided into five stages: take-off, climb, cruise, descent, and landing. The boundary conditions for each stage are listed in Table 8.

Table 8 Flight Profile

	Take Off	Climb	Cruise	Descent	Landing
Time (s)	120	120-520	520-1420	1420-1670	1670-1770
Power (W)	0-150	150-20	20	20-120, 120-60	60-20
Cabin temperature(°C)	70-60	60-135	135	135-75	75-60
Inlet temperature of coolant(°C)	80-88	88-102	102-120	120	120
Inlet temperature of the hydraulic oil. (°C)	90-95	95-105	105-110	110	110

As shown in Fig. 7, the temperature variation of the motor housing is simulated across the flight profile.

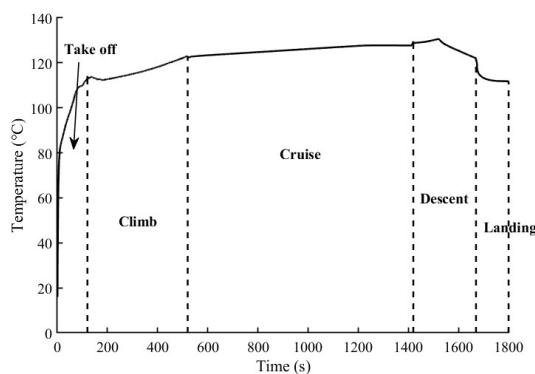


Fig. 7 The Result of Full Flight Profile Simulation

In the take off phase, the duration of take off is 120 seconds. During take off, the actuator output power is relatively high, with the maximum heat generation power reaching 150W. The ambient temperature is around 60°C, the coolant inlet temperature is 80°C, and the internal hydraulic oil temperature is 90°C. As the aircraft starts, the actuator output power gradually increases, reaching the maximum heating power of 150W, causing the motor temperature to continuously rise. The housing temperature reaches 110°C, the stator temperature gradually increases to 115°C, the winding temperature rises to around 116°C, and the rotor temperature increases to about 114°C. Although the ambient temperature is relatively low during this phase, the actuator's large output power leads to a high heat generation rate, causing a significant temperature rise in the permanent magnet motor.

In the climb phase, the climb time is 400 seconds. During this phase, the actuator output power gradually decreases, but the ambient temperature rises from 60°C to 135°C. The inlet temperature of the coolant is 88°C, rising to 102°C as the flight time increases, and the hydraulic oil temperature increases from 95°C to 105°C. During this phase, the actuator output power gradually decreases, reducing the motor heat generation. The motor temperature starts to drop. However, due to the rise in ambient temperature, coolant temperature, and hydraulic oil temperature, the motor temperature initially decreases slightly, then continues to rise. Finally, the housing temperature stabilizes at around 123°C, the stator temperature is around 107°C, the winding temperature is around 106°C, and the rotor temperature is around 107°C.

In the cruise phase, the cruise time is 900 seconds. Since there are no operational requirements during this phase, the actuator maintains a low power state with a heat generation power of 20W. The ambient temperature remains at 135°C. The coolant gradually absorbs heat from the aircraft's electronic equipment, causing a significant rise in temperature. The coolant inlet temperature rises from 102°C to 120°C, and the hydraulic oil inlet temperature gradually increases to 110°C. During the cruise phase, the actuator output power is relatively low. The motor's heat generation power is about 20W, and the heat generation is small. As a result, the motor temperature is more influenced by the ambient temperature, coolant inlet temperature, and hydraulic oil temperature. The housing temperature is around 122°C, the stator and winding temperatures are around 119°C, and the rotor temperature is around 113.5°C. Although the motor's internal heat generation is small, the rising temperature of the coolant causes the motor's overall temperature to gradually increase. The rotor temperature is lower than the stator and winding temperatures due to the lower hydraulic oil temperature inside the motor.

In the descent phase, the descent time is 250 seconds. During this phase, the actuator output power first increases and then decreases. The heat generation power rises to 120W and then decreases to 60W. The ambient temperature gradually decreases from 135°C to 70°C, and the coolant inlet temperature remains unchanged at 120°C, while the hydraulic oil inlet temperature is 110°C. During the descent phase, the external ambient temperature gradually decreases, while the coolant and hydraulic oil inlet temperatures are at their highest. After the actuator output power increases and then decreases, the permanent magnet motor heat generation power reaches 120W. The housing, stator, and winding temperatures gradually increase, with the housing temperature reaching 128°C, the stator temperature reaching 123°C, and the winding temperature reaching 124°C. The rotor temperature remains lower than the other parts due to the lower hydraulic oil temperature compared to the ambient temperature and coolant inlet temperature. When the actuator output power decreases, the temperatures of all parts start to decrease. Since the coolant temperature remains at 120°C, the motor temperatures stabilize at around 116.5°C, with the rotor temperature at around 113°C.

In the landing phase, the landing time is 230 seconds. During this phase, the actuator output power is very low, with the permanent magnet motor heat generation power reduced to 20W. The ambient temperature decreases from 75°C to 60°C, and the housing temperature drops to 115°C. The coolant temperature remains at 120°C, and the internal hydraulic oil temperature is 110°C.

The transient simulation results show that throughout the flight profile, the temperature of all part of motor remains below 135°C. This indicates that the Z-shaped water channel cooling structure effectively keeps the motor temperature within the ideal range.

CONCLUSIONS

To address the severe thermal management challenges faced by electro-hydrostatic actuator motors in hypersonic aircraft under extreme aerodynamic heating and high-power loads, this paper proposes a novel axially integrated Z-shaped liquid cooling channel, supported by mathematical modeling and optimization. Aiming to resolve the issue of localized overheating caused by uneven heat dissipation in traditional cooling structures under extreme conditions, the following main conclusions are drawn based on computational fluid dynamics simulations:

1. Simulations of the natural-convection baseline condition reveal that under an ambient temperature of 135 °C, passive cooling fails as the internal oil temperature approaches that of the solid components, leading to severe thermal runaway. The winding and magnet temperatures reach approximately 181 °C and

176 °C, respectively, significantly exceeding safe operating limits. These results quantitatively confirm that incorporating an efficient active liquid cooling system is indispensable for ensuring the safe operation of the actuator in hypersonic applications.

2. Comparative simulations between the proposed axially integrated Z-shaped channel and the original coil-shaped channel demonstrate that under the attitude-adjustment condition, the Z-shaped channel reduces the average housing, stator, and winding temperatures by 4.1%, 9.2%, and 8.6%, respectively, compared to the coil-shaped channel. Under the peak-load condition, these temperatures are reduced by 3.6%, 10.9%, and 4.6%, respectively. Crucially, the Z-shaped geometry eliminates the local hot spots observed in the winding region of the coil-shaped design, successfully maintaining the maximum winding temperature below 130 °C, thereby validating the effectiveness of the proposed design in mitigating localized overheating.

3. The analysis indicates that the enhancement in heat dissipation comes at the cost of higher hydraulic resistance. At identical inlet conditions, the pumping power requirement for the Z-shaped channel increases by approximately 78% in both operating conditions. However, given that the cooling circuit operates independently and the results demonstrate a significant improvement in thermal safety margins and the prevention of demagnetization risks, this increase in pumping power is considered an acceptable engineering trade-off.

4. Transient simulations over the full flight profile confirm the robustness of the design under time-varying boundary conditions. With the adoption of the Z-shaped channel, the temperatures of all critical motor components remain strictly below the 135 °C safety limit throughout the takeoff, climb, cruise, descent, and landing phases, with the maximum housing temperature limited to approximately 128 °C, ensuring thermal reliability across the entire mission profile.

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