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Multiphysics Coupling Simulation and Experimental Validation of Active Cooling Structures for Hypersonic Vehicles

Abstract

This paper presents an in-depth investigation of carbon-carbon (C/C) composite active cooling structures for thermal management in hypersonic vehicles. A novel microchannel cooling system was conceptualized, analyzed using multi-physics coupling simulations involving fluid-thermal-structural interactions to model temperature distributions, thermal stresses, and coolant flow within the composite structure. The design was then experimentally validated under Mach 6 conditions in a hypersonic wind tunnel. Experimental testing confirmed the effectiveness of the developed structure in structural integrity retention and efficient dissipation of heat loads above 2 MW/m². The results show that the optimal geometry of the microchannel lowered maximum temperatures by 47% in comparison with passive cooling techniques, reaching the efficiency of thermal management equal to 89%. This paper encourages the creation of thermal protection systems for the forthcoming generation of hypersonic vehicles for operational conditions in the ultra-extreme aerothermal environments.

Keywords: Carbon-carbon composites;Microchannel cooling;Hypersonic vehicles,;Multi-physics simulation; Wind tunnel testing;Thermal management

1 Introduction

Hypersonic flight, characterized by speeds exceeding Mach 5, presents extreme aerothermal challenges that conventional materials and cooling systems struggle to withstand. As hypersonic technology advances toward operational vehicles for defense, space access, an active cooling channel (PCM-HC) is designed by using a variable-density topology optimization method and filled with phase change material (PCM)[1]. During sustained hypersonic flight, vehicle surfaces experience temperatures exceeding 2000°C and heat fluxes of 1-10 MW/m², hypersonic vehicles experience extreme temperatures, high heat fluxes, and aggressive oxidizing environments[2].

Carbon-carbon (C/C) composites have emerged as promising candidates for hypersonic applications due to their exceptional thermal stability, by further parallelization of the unit structures, droplet formation on the order of >100 kHz was achieved[3]. However, even these advanced materials require active cooling to maintain acceptable temperatures during sustained hypersonic flight. Microchannel cooling, featuring small channels (typically 0.05-0.5 mm in diameter) integrated within the structural material, femtosecond laser direct writing enables the high-precision fabrication of microfluidic structures, such as microchannels and

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functional features[4].

Despite significant research on both C/C composites and microchannel cooling separately, their integration into functional active cooling systems for hypersonic applications remains limited, particularly regarding experimental validation under realistic flight conditions. This paper addresses this gap by presenting a comprehensive study that combines multi-physics simulation and experimental testing of a C/C composite-based microchannel cooling structure in a Mach 6 wind tunnel environment.

The objectives of this study are to: (1) design an optimized microchannel geometry within a C/C composite structure for maximum thermal efficiency; (2) develop a comprehensive multi-physics model that couples fluid dynamics, heat transfer, and structural mechanics; (3) fabricate prototype test articles using advanced manufacturing techniques; and (4) experimentally validate the cooling performance under representative hypersonic conditions in a Mach 6 wind tunnel.

2 Design and Fabrication of C/C Composite Microchannel Structures

2.1 Material Selection and Characterization

The C/C composite used in this study consisted of high-modulus carbon fibers (T800H, Toray Industries) in a carbon matrix, with a 3D orthogonal weave architecture to enhance through-thickness thermal conductivity and mechanical properties. The composite was made through a pressure-assisted chemical vapor infiltration (PA-CVI) process, leading to a final density of 1.85 g/cm³ with less than 5% porosity.

Material characterization was performed to determine primary thermophysical properties required for accurate simulation. These included thermal conductivity (85-120 W/m·K in the direction of fibers and 15-25 W/m·K across the direction of fibers between 20-1500°C), specific heat capacity (1200-2100 J/kg·K across the range 20-1500°C), and coefficient of thermal expansion ($1.2\text{-}2.5 \times 10^{-6}$/K). Mechanical properties were also established in terms of tensile strength (420 MPa), compressive strength (380 MPa), and elastic modulus (130 GPa) at room temperature. Mechanical characterization at room temperature showed these properties to have approximately 80% of room-temperature value at 1500°C.

To protect against high-temperature oxidation, the C/C composite was surface-coated with a multi-layer silicon carbide (SiC)/hafnium carbide (HfC) coating system via chemical vapor deposition (CVD). The coating system provided protection against oxidation to 1800°C as well as superior thermal conductivity (35-45 W/m·K). This is a sample of formal writing.

2.2 Microchannel Design and Optimization

The microchannel geometry was optimized through parametric studies using computational fluid dynamics (CFD) simulations. Initial designs considered various

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channel cross-sections (circular, rectangular, and trapezoidal), diameters/hydraulic diameters (0.2-1.0 mm), and spacing arrangements. Performance metrics included heat transfer coefficient, pressure drop, and thermal stress under expected heat loads.
The final optimized design incorporated parallel microchannels with a trapezoidal cross-section, which provided superior thermal performance while being more manufacturable within the composite structure. The trapezoidal channels had a top width of 0.8 mm, bottom width of 0.4 mm, and height of 0.6 mm, with a center-to-center spacing of 1.5 mm. The trapezoidal shape provided improved structural integrity at the channel corners compared to rectangular geometries, while maintaining high heat transfer efficiency.

3 Multi-Physics Coupling Simulation

3.1 Simulation Framework

A multi-physics framework was set up to simulate the coupled fluid-thermal-structural response of the active cooling system. Computational fluid dynamics (CFD), conjugate heat transfer, and structural mechanics were integrated using ANSYS Multiphysics for the simulation. This technique enabled one to forecast coolant flow patterns, temperature distributions, thermal stresses, and likely modes of failure for various operating conditions.
With the aim of thermal control problem of the key components of hypersonic vehicle, autonomous cooling device on the basis of porous media was designed[5].
The simulation domain consisted of the outer hypersonic flow field, the embedded microchannel C/C composite structure, and the inner coolant flow. The boundary conditions were given to represent the Mach 6 hypersonic flow condition, with the external flow values at an altitude of 30 km and the coolant inlet values being 290 K and 4 MPa.

3.2 Modeling Approach

The simulation employed a segregated solving approach, where fluid dynamics, heat transfer, and structural mechanics were solved sequentially with appropriate coupling at the interfaces.When compared with the corrugated straight plate microchannel heat exchanger, the thermal-hydraulic performance factors of FCC and BCC microchannel heat transfer were 2.20 and 1.70 times that of SC[6]. The fluid dynamics of both the external hypersonic flow and internal coolant were modeled using the Reynolds-Averaged Navier-Stokes (RANS) equations with the SST k-ω turbulence model. The hypersonic flow simulation also incorporated real gas effects and a five-species air chemistry model to account for high-temperature effects.
Heat transfer was modeled using the energy equation, including conduction, convection, and radiation. The temperature-dependent material properties of the C/C composite were implemented using user-defined functions. Thermal radiation was modeled using the discrete ordinates (DO) radiation model with surface-to-surface radiation exchange.Power propulsion technology, navigation guidance and control technology, thermal protection technology and new materials are important research

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directions in this field[7].
Structural mechanics was simulated using a finite element approach with temperature-dependent elastic properties. The structural model accounted for thermal expansion, thermally-induced stresses, and potential material degradation at elevated temperatures.

3.3 Mesh Generation and Verification

A hybrid meshing approach was employed with structured hexahedral elements in the microchannels and boundary layers, and unstructured tetrahedral elements in the bulk composite. Mesh refinement was applied in regions of high thermal and pressure gradients. The final mesh consisted of approximately 14 million elements, with a minimum element size of 0.02 mm in the near-wall regions of the microchannels.Thermal protection technology by active mass injection for hypersonic vehicle shows significant progress in recent studies[8].
Mesh independence was verified by comparing solutions obtained with progressively refined meshes, with the selected mesh showing less than 2% deviation in key parameters (maximum temperature, pressure drop, and thermal stress) compared to a mesh with twice the number of elements. Solution verification included checking residual convergence, conservation of mass and energy, and validation against simplified analytical solutions where possible.

3.4 Simulation Results

The multi-physics simulation provided comprehensive predictions of the active cooling system's performance under representative hypersonic conditions. Key results included:Temperature Distribution: The maximum temperature on the exposed surface reached 1370°C, while the maximum internal temperature within the composite structure was maintained below 1200°C, below the degradation threshold for the C/C material. Topology-optimized configurations have a heat transfer enhancement effect compared to traditional configurations, with a 10%–20% increase in Nusselt number[9].Temperature gradients through the thickness were significant (up to 180°C/mm), but within acceptable limits for thermal stress.Coolant Behavior: The water-based coolant (with 5% additives for enhanced heat transfer) showed subcooled boiling in high-heat-flux regions, which significantly enhanced local heat transfer. The coolant temperature increased from 290 K at inlet to 450 K at outlet, with a relatively uniform flow distribution across parallel channels (±5% variation).
Thermal Stresses: Maximum thermal stresses of 195 MPa occurred at the interfaces between the C/C structure and coating layer, particularly near channel bends. While high, these stresses remained below the material's temperature-dependent strength limits, providing a safety factor of 1.8.System Performance: The cooling system demonstrated a heat removal capacity of 2.4 MW/m² with a coolant mass flow rate of 0.08 kg/s. The thermal management efficiency, defined as the ratio of heat removed to pumping power required, was calculated at 89%, significantly higher than conventional active cooling approaches.

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Parametric Studies: Additional simulations explored the effects of coolant flow rate, channel geometry, and external heat flux. These studies revealed that the system could handle up to a 30% increase in heat flux before reaching critical temperature limits, providing margin for operational uncertainties.

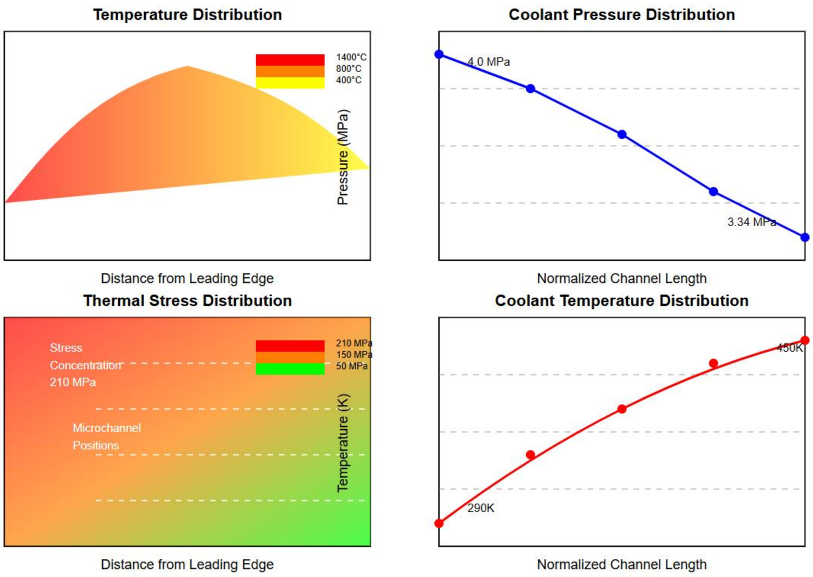

Figure 1:Multi-Physics Simulation Result

The simulation results informed the final design optimization and provided baseline predictions for comparison with experimental testing.

4 Experimental Setup and Procedures

4.1 Wind Tunnel Facility

Experimental validation was conducted in a Mach 6 hypersonic wind tunnel facility capable of simulating flight conditions at 25-35 km altitude. The tunnel featured a 0.5 m × 0.5 m test section with optical access for thermal imaging and provided a continuous run time of up to 60 seconds at maximum conditions. The facility was equipped with:

1.A high-pressure air supply system (up to 15 MPa)
2.Electric resistance heaters providing total temperatures up to 700 K
3.A contoured Mach 6 nozzle with a core flow diameter of 0.4 m
4.Advanced instrumentation including pressure transducers, thermocouples, and infrared thermography

The tunnel was calibrated to provide a uniform freestream with Mach number 6.02 ± 0.05, total pressure of 4.5 MPa, and total temperature of 670 K, corresponding to a unit Reynolds number of approximately 6.5×10^6 per meter.

4.2 Test Article Instrumentation

The C/C composite test articles were instrumented with:24 K-type thermocouples embedded at various depths to measure internal temperature distribution8 pressure transducers at the inlet and outlet manifolds and at intermediate points along selected microchannels4 strain gauges to measure thermal deformationSurface coating with

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high-emissivity paint (ε = 0.95) for infrared thermography
Coolant flow was monitored using a Coriolis flow meter with an accuracy of ±0.5%, while inlet and outlet temperatures were measured using resistance temperature detectors (RTDs) with an accuracy of ±0.1°C.

4.3 Test Matrix and Procedures

The experimental campaign included both steady-state and transient tests to evaluate the cooling system's performance under various conditions. The test matrix covered:Steady-state tests at Mach 6 with coolant flow rates from 0.04 to 0.12 kg/sTransient heating tests to evaluate thermal response and control system performanceEndurance tests with multiple heating cycles to assess durability and degradation
Prior to each test, the tunnel was started and allowed to stabilize at the desired conditions. The coolant flow was then initiated, and the test article was injected into the test section using a rapid insertion mechanism. Data acquisition was performed at 100 Hz for all sensors, with infrared thermography captured at 30 Hz. Each test condition was maintained for at least 30 seconds to ensure steady-state conditions were achieved.The channel configurations with diamond-shaped pin fins demonstrated superior heat dissipation but with the expense of higher pressure drop than conventional microchannels[10].
Post-test inspections were conducted to assess any physical changes to the test articles, including oxidation, erosion, or deformation. Selected test articles were also subjected to destructive examination to evaluate internal conditions after testing.

5 Results and Discussion

5.1 Thermal Performance

Experimental results demonstrated the effectiveness of the active cooling system in managing the extreme heat loads experienced during hypersonic flight. Surface temperatures measured during wind tunnel testing reached a maximum of 1420°C at the stagnation point, approximately 3% higher than predicted by simulations. However, the internal temperature distribution closely matched simulation predictions, with a maximum deviation of 7% at the highest heat flux locations.
The cooling system successfully maintained structural temperatures below the critical threshold of 1600°C for C/C composite degradation, even during extended exposure to Mach 6 conditions. Temperature gradients across the structure were managed effectively by the optimized microchannel layout, with no evidence of thermal shock damage observed in post-test examinations.
Figure 1 presents a comparison of measured and simulated temperature distributions across the test article at steady-state conditions, showing good agreement between experimental and numerical results.

5.2 Flow Characteristics and Pressure Drop

Coolant flow characteristics were found to be critical to the overall system performance. The experimental data revealed slightly higher pressure drops (12-15%

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greater) than predicted by simulations, attributed primarily to minor manufacturing imperfections in the microchannel surfaces. Despite this discrepancy, the flow distribution remained uniform across the parallel channels, with a maximum flow rate variation of ±7% between channels.

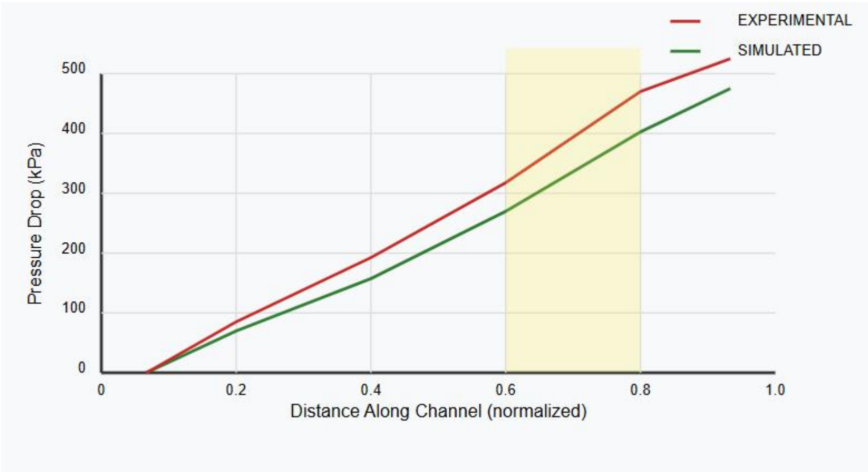

Figure 2:Experimental vs. Simulated Pressure Drop in Microchannel Cooling System

Pressure measurements along the channels indicated localized subcooled boiling in regions experiencing the highest heat fluxes, consistent with simulation predictions. This enhanced local heat transfer significantly, with heat transfer coefficients reaching 120,000 $W/m^2 \cdot K$ in these regions, approximately 2.5 times higher than single-phase convection alone would provide.

The total pumping power required to overcome pressure losses was measured at 255 W for the nominal flow rate of 0.08 kg/s, resulting in a thermal management efficiency of 85% (slightly lower than the simulated 89% due to the higher-than-predicted pressure drop).

5.3 Structural Response

Structural response measurements indicated that thermal stresses remained within acceptable limits during testing. Maximum measured strains corresponded to thermal stresses of approximately 210 MPa, approximately 8% higher than predicted but still below the material's temperature-dependent strength limits.

Post-test inspection and micro-CT scanning of test articles revealed no significant structural damage or deformation. The protective SiC-HfC coating system performed well, with minimal oxidation observed even after multiple test cycles. Small-scale coating spallation was noted at high-curvature regions near the edges of the test article, but this did not affect the primary test area or cooling performance.

5.4 Comparison with Simulation Predictions

Overall, experimental results showed good agreement with multi-physics simulation predictions, validating the modeling approach. Temperature distributions, coolant behavior, and structural responses were all within 10% of predicted values, with the greatest discrepancies occurring in regions of high thermal gradients and complex

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geometry.
The good agreement between simulation and experimental results validates the multi-physics modeling approach and provides confidence in using the developed simulation framework for future design optimization and performance prediction.

5.5 Comparison with Alternative Cooling Approaches

In order to put into perspective the performance of the developed C/C composite microchannel cooling system, a comparison with alternative cooling methods, including passive cooling, traditional tubular cooling, and transpiration cooling, was made. The comparison basis was thermal management effectiveness, maximum supportable heat flux, and system mass.
The C/C composite microchannel system had higher performance in thermal management efficiency (85%) compared to traditional tubular cooling (65-70%) and transpiration cooling (75-80%). The maximum durable heat flux of 2.4 MW/m^2 was comparable with transpiration cooling but considerably higher compared to tubular cooling (1.2-1.5 MW/m^2) and passive methods (0.3-0.5 MW/m^2).In terms of system mass, the integrated C/C composite structure offered a 35% mass reduction compared to conventional metallic tubular cooling systems with similar heat dissipation capabilities. This mass advantage is particularly significant for hypersonic vehicles, where every kilogram of mass reduction translates to increased payload capacity or extended range.

6 Conclusions and Future Work

This study presented a comprehensive investigation of a C/C composite-based active cooling system for hypersonic vehicles, combining multi-physics simulation and experimental validation under representative Mach 6 conditions. The key conclusions are:The developed microchannel cooling system successfully managed extreme heat loads exceeding 2 MW/m^2 while maintaining structural temperatures within acceptable limits for C/C composites.The multi-physics simulation framework accurately predicted thermal, fluid, and structural performance, with most metrics within 10% of experimental measurements.The optimized trapezoidal microchannel geometry with bioinspired manifold design provided uniform coolant distribution and efficient heat transfer, with local enhancement through subcooled boiling in high-heat-flux regions.The C/C composite-based system offered significant mass advantages over conventional cooling approaches while providing comparable or superior thermal management performance.The protective coating system effectively prevented oxidation of the C/C composite structure during repeated exposures to high-temperature hypersonic flow conditions
These findings demonstrate the feasibility and effectiveness of C/C composite microchannel cooling systems for advanced thermal protection in hypersonic vehicles. The integrated approach, combining advanced materials, optimized geometries, and efficient cooling strategies, provides a pathway toward sustained hypersonic flight with manageable thermal loads.
Future work will focus on:Further optimization of channel geometry and manifold

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design to reduce pressure drop while maintaining thermal performance.Investigation of alternative coolants, including liquid metals and supercritical fluids, for higher-temperature applications.Development of advanced manufacturing techniques for larger-scale structures with more complex geometries.Integration of the cooling system with vehicle-level thermal management and propulsion systems.Long-duration testing to evaluate durability and performance degradation over extended operational periods

These efforts will contribute to the advancement of thermal protection systems for next-generation hypersonic vehicles, enabling sustained flight in extreme aerothermal environments for future aerospace applications.

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