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Research on Nonlinear Numerical Simulation Methods for Heat Transfer Characteristics of High-Temperature Devices

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Abstract With the rapid development of aerospace and electronics industry, the thermal management of high-temperature devices has become a key bottleneck restricting the progress of the industry. Based on the theoretical foundation of nonlinear partial differential equations, this study innovatively combines the improved Khater method with the precalibration algorithm to construct a set of hybrid numerical simulation methods for the heat transfer characteristics of high-temperature devices, which shows excellent computational accuracy and numerical stability when dealing with the region of drastic temperature changes. In order to solve the problem of heat dissipation in high temperature environments, this paper designs a device heat dissipation scheme with a fractal wave wall structure, which is corroborated by systematic numerical simulations and experimental tests. The research data show that the optimized fractal wavefront structure achieves a significant improvement of 23.7% in heat transfer efficiency at a high temperature of 600°C, while the uniformity of temperature distribution is significantly improved. The experimental measurements are in high agreement with the numerical simulation predictions, which not only confirms the reliability of the proposed hybrid numerical method, but also verifies the effectiveness of the fractal wave-wall structure design in practical applications. This study not only enriches the theoretical system of thermal management of high-temperature devices, but also provides a feasible technical path for related engineering practice, which has important theoretical value and broad engineering application prospects in high-temperature applications such as aerospace and electronics manufacturing.

Index Terms high-temperature device, heat transfer, nonlinear partial differential equation, numerical simulation, fractal wave wall structure

I. Introduction

I. A. Background and significance of the study

In the context of the booming development of modern aerospace and electronics industries, the issue of thermal management of high-temperature devices is becoming more and more prominent. High-temperature devices are key components of modern industry, and their temperature management is directly related to device reliability and efficiency. Aerospace advanced power units, high-temperature physical exploration instruments and automotive electronics, these devices often work in harsh environments and are very sensitive to temperature changes. If the temperature exceeds the safe range, it will cause a sharp decline in performance, and even lead to irreparable damage. Complex high-temperature device operating environment, the heat transfer process presents obvious nonlinear characteristics. Take the silicon carbide power devices, its thermal resistance with the temperature rise shows nonlinear changes, this feature makes the device actual heat dissipation performance and the traditional linear model prediction results have a large gap. The traditional linear heat conduction theory is no longer able to accurately describe such complex thermal phenomena, and researchers must find more accurate mathematical expressions. Nonlinear partial differential equations (PDEs) can accurately characterize the complex physical processes and show unique advantages in the study of heat transfer in high-temperature devices. The application of such equations not only enhances model accuracy, but also provides a theoretical basis for optimizing heat dissipation design. These equations can effectively capture nonlinear effects such as temperature dependence, material nonuniformity, and interfacial thermal resistance, and provide a reliable theoretical basis for the thermal management design of high-temperature devices. However, due to the complexity of solving nonlinear partial differential equations, how to quickly and accurately obtain the equation solution and apply it to practical engineering has become the focus and difficulty of current research.

To address the above problems, this paper is based on nonlinear partial differential equations to study the heat transfer characteristics of high-temperature devices. By constructing a reasonable mathematical model, using improved numerical methods for simulation and analysis, combined with experimental verification, the aim is to provide reliable theoretical guidance for the design of high-temperature device thermal management. This study is of great significance to improve the reliability and service life of high-temperature devices, as well as to provide new ideas and methods for technological innovation in related fields. The importance of this research is reflected in the provision of more accurate theoretical guidance for the thermal management design of high-temperature devices, and the improvement of the numerical simulation method, which improves the efficiency and accuracy of solving nonlinear partial differential equations. The research results can be directly used for the design and optimization of high-temperature devices in aerospace, automotive electronics and other fields, which has important engineering application value.

I. B. Main contributions and innovations

In this study, we have conducted an in-depth research on the problems of insufficient computational accuracy and poor stability in the heat transfer characterization of high-temperature devices. For solving nonlinear partial differential equations, we propose a hybrid numerical computation method that combines the improved cartel method with a precalibration algorithm. The improved cartel method overcomes the problem of accuracy degradation of the traditional method when dealing with strong nonlinear terms by introducing Jacobi elliptic function expansions, which makes the method perform well in capturing the nonlinear heat transfer characteristics of high-temperature devices with drastic temperature changes. In terms of the precalibration algorithm, we have improved the traditional Adams-Bashford prediction and Adams-Morton correction techniques by proposing a precalibration algorithm with multiple corrections along with an alternating forward and backward correction algorithm. This improvement makes it possible to maintain good computational accuracy at large time steps, and the algorithm does not need to solve higher-order systems of equations, with simple programming implementation and low memory consumption.

In terms of structural design, we have designed a novel structural optimization scheme for high-temperature devices inspired by wave-wall microchannel heat dissipation technology. This scheme combines the concept of fractal wave-wall design with the synergistic mechanism of pulsating flow field. By introducing a specific wave structure in the heat dissipation channel of the device, the heat exchange efficiency between the fluid-solid interface is significantly improved, and the temperature distribution on the wall surface is more uniform. This design cleverly utilizes the synergistic effect of the flow channel structure and the flow field characteristics to optimize the heat transfer performance without increasing additional energy consumption. Aiming at the problem of high computational complexity, we propose a non-linear partial differential equation dynamic system dimension reduction method based on the optimization method. The method effectively reduces the computational complexity by optimizing the energy error function of the high-dimensional and low-dimensional systems while preserving the nonlinear dynamics characteristics of the system.

In order to verify the practicality of the present research results, we built a high-temperature device heat transfer characteristics test platform for system verification. Through the comparison and analysis of experimental and simulation results, our numerical method and optimization design show good feasibility in practical applications.

I. C. Literature review

As the integration of electronic devices continues to increase, their power density continues to increase and they face increasingly severe thermal failure problems [1]. According to a U.S. Air Force report, more than 50% of the failures of electronic devices are caused by temperature [2]. High temperatures can cause electronic devices to suffer from solder joint fatigue, solder joint detachment, bond wire fracture, dielectric film fracture, delamination, chip fracture and other problems, leading to a decline in the performance of the electronic device or even failure, and a significant reduction in the life of the device [3], [4]. Therefore, high temperature is an important factor restricting the development of electronic devices, so the research on high temperature devices has become more and more important.

The heat dissipation technology of electronic devices under ambient conditions is relatively mature, and its basic principle is to transfer the self-generated heat of electronic devices to the environment through thermal conductivity, convection or radiation heat transfer [5]. On the contrary, for extreme occasions with high ambient temperatures, such as oil logging, aerospace, and military fields, the external ambient temperature is higher than the temperature of the electronic device, and the self-generated heat of the electronic device can not be distributed to the environment, and the high-temperature environment accelerates the temperature rise of the electronic device [6]-[9]. Therefore, different from the characteristics of heat transfer of electronic devices at room temperature, the heat transfer of electronic devices in high temperature environment mainly adopts thermal insulation measures to protect the high temperature electronic devices to avoid the influence of the external high temperature environment, and at the same time, the self-generated heat of electronic devices is temporarily stored [10]-[12].

In order to enable the electronic devices to work for a long time in the high temperature environment, it can be processed in two ways. One is the use of chips made of silicon-based materials with high temperature resistance, which can enhance the tolerable temperature of electronic devices to some extent [13]. The second is to control the temperature of the electronic device within its temperature tolerance range through heat transfer management programs [14]. For high-temperature chips, the manufacturing cost is generally high, and the packaging is difficult, and high-temperature reliability is also a problem. In contrast, thermal transfer management schemes can make electronic devices work stably within the temperature range, and are relatively low cost and universal [15], [16]. Therefore, there is an urgent need to study the heat transfer characteristics of high-temperature devices.

The research field of heat transfer characteristics of high-temperature devices has made significant progress in recent years, but there are still a number of difficult problems that need to be solved.

II. Research methodology

II. A.Improved Khater's method and precalibration algorithm

The heat transfer process of high-temperature devices presents significant nonlinear characteristics, and traditional numerical methods often face difficulties of insufficient accuracy and computational instability when dealing with such problems. To address these problems, we propose a hybrid numerical method that combines the improved Khater method with a precalibration algorithm to improve the accuracy and stability of solving nonlinear partial differential equations. The improved Khater method is based on the Jacobi elliptic function expansion, and the strong nonlinear characteristics of the heat transfer process of high-temperature devices are effectively dealt with by introducing special functions to construct the exact solution. Namely:

$$u(x,t)=\sum_{n=0}^{\infty}a_nJ_n(\lambda x)e^{-\lambda^2 t} \tag{1}$$

where J_n represents the n-order Bessel function, which describes the spatial distribution characteristics of the heat transfer process; λ is the eigenvalue, which is closely related to the boundary conditions; and a_n is the coefficient to be determined, which is determined by satisfying the initial conditions. Compared with the traditional (G' /G)-expansion method, the improved Khater's method introduces a more flexible function basis, which can accurately capture the spatial distribution characteristics of the temperature field, and performs particularly well in the region of drastically changing temperature gradients.

When dealing with the time evolution problem, the improved precalibration algorithm is used in this study. The algorithm is based on the Adams-Bashforth prediction and Adams-Moulton correction techniques, and the computational accuracy is improved by multi-step iteration. The core formula of the precalibration algorithm is:

$$u_{n+1}=u_n+\Delta t[\tfrac{3}{2}f(u_n)-\tfrac{1}{2}f(u_{n-1})] \tag{2}$$

where u_n denotes the numerical solution at the nth step, Δt is the time step, and $f(u)$ is a nonlinear function describing the system dynamics. We make two improvements to the precalibration algorithm: we introduce a multiple correction mechanism to reduce the truncation error through iterative correction; and we adopt an alternating positive and negative correction strategy to effectively suppress numerical oscillations. These improvements enable the algorithm to maintain good computational accuracy and stability at large time steps. In practical applications, we use the improved Khater method to deal with the spatial discretization and transform the partial differential equations into a system of ordinary differential equations; subsequently, we use the improved precalibration algorithm to solve the time evolution problem.

This hybrid algorithm gives full play to the advantages of the two methods, ensures a high-precision description of the spatial distribution, and ensures the stability of the time evolution. By comparing and analyzing with the traditional finite difference method and finite element method, the hybrid algorithm shows higher computational accuracy and better numerical stability when dealing with the heat transfer problem of high-temperature devices, especially when dealing with the region of drastically changing temperature gradient and the problem of long time evolution. The algorithm does not need to solve higher-order equations, is simple to implement and consumes less memory, and provides a powerful tool for efficient numerical simulation of heat transfer characteristics of high-temperature devices. Our study shows that the hybrid strategy combining spatially accurate solution construction and time-efficient integration can effectively solve the computational challenges in the simulation of heat transfer in high-temperature devices and provide new ideas for numerical simulation research in related fields.

II. B.High temperature device structure optimization design

In order to solve the problem of insufficient heat dissipation efficiency in high-temperature devices, we propose an innovative optimization scheme based on a fractal wave-wall structure, which is inspired by the characteristics of the branching system of biological blood vessels, and develops a new type of heat dissipation channel structure by combining the fractal theory with the principle of fluid dynamics. The core of the scheme is a multi-stage branching fractal wave-wall channel design, in which the size ratio between the main channel and the branch channels follows the golden section, which not only ensures the uniform distribution of fluid in each channel, but also demonstrates the best heat transfer performance in the numerical simulation by the precisely calculated 0.15 wave amplitude to wavelength ratio. To further optimize the structural performance, an inlet-to-outlet gradient ratio of 1.2:1 is adopted in the channel cross-section, which reduces the fluid resistance and enhances the turbulence perturbation effect at the same time. At the same time, a micron-sized groove array is introduced on the wave wall surface to enhance the heat exchange area. In the optimization of pulsation flow field parameters, through a large number of simulation experiments, it is found that when the Reynolds number is in the range of 2000-3000, the parameter combination of setting the pulsation frequency at 15-20Hz and maintaining the amplitude at 30% of the steady-state flow rate can achieve the optimal heat exchange efficiency without significantly increasing the energy consumption of the system.

In order to comprehensively enhance the heat dissipation effect, we adopt the nano-coating technology in the material interface treatment, through the deposition of 100nm thickness of alumina nano-coating on the inner surface of the wave-wall channel, which not only improves the wettability of the surface and the thermal conductivity, but also enables the interface thermal resistance to be significantly reduced, and at the same time, enhances the corrosion resistance of the material.

III. Results and discussion

III. A. Experimental platform construction and validation

In order to verify the effectiveness of the improved Khater method mixed with precalibration algorithm and the optimized design of high-temperature device structure proposed in this paper, we constructed a set of precise test platform for heat transfer characteristics of high-temperature devices. The platform contains four parts: high-temperature heating system, precise temperature measurement system, cooling circulation system and data acquisition system, in which the high-temperature heating system adopts a programmable resistance heater with a temperature control accuracy of ±0.5℃ and a maximum working temperature of up to 800℃, which is able to simulate high-temperature working conditions in extreme environments such as aerospace. The temperature measurement system consists of 20 K-type thermocouples forming a temperature measurement array, distributed on the surface of the device in key locations, through the 16-bit high-precision data acquisition card to monitor the temperature field distribution in real time, with a sampling frequency of 10Hz, and a temperature measurement accuracy of better than ± 0.2 ℃. The cooling circulation system adopts a closed-loop design, equipped with a precision flow control device, with a flow range of 0.1-2.0L/min and a control accuracy of ±0.02L/min, ensuring the stability and repeatability of the experimental conditions. The experimental samples include two kinds of traditional straight-wall structure and optimized fractal wave-wall structure, all of which are made of high-purity 4H-SiC material, with the size of 20mm × 20mm × 2mm, and a miniature heating element is integrated at the bottom of the samples, which can provide an adjustable heat flow density of 10-100W/cm², and the ambient temperature, the coolant flow rate, the heating power, and other parameters are strictly controlled in the process of the experiments, to ensure the consistency of the experimental conditions with the numerical simulation settings. The experimental conditions are consistent with the numerical simulation settings, and each group of experiments is repeated three times, taking the average value as the result to eliminate the effect of random error.

Comparison between experimental results and numerical simulation results is shown in Table 1, where the experimentally measured temperature field distributions are highly consistent with the numerical simulation predictions under different working conditions, and the errors are controlled within 1%, which verifies the accuracy and reliability of the hybrid numerical method proposed in this paper. In particular, under the high temperature environment of 600°C, the maximum temperature of the optimized fractal wave-wall structure is 42.2°C lower than that of the traditional straight-wall structure, and the heat transfer efficiency is improved by 23.7%, which is very close to the 23.9% predicted by the simulation, which confirms the validity of the optimized structural design. Through the long-term stability test, it is found that after 100 hours of continuous operation in a 600℃ high-temperature environment, the heat transfer performance of the fractal wave-wall structure decays by only 4.8%, which is much lower than that of the straight-wall structure (12.3%), indicating that the optimized design has good long-term stability. In-depth analysis reveals that the performance improvement is mainly attributed to the complex turbulence structure formed by the fractal wave wall structure at the fluid-solid interface, which effectively breaks the thermal boundary layer and enhances the convective heat transfer effect. The synergistic effect of the pulsating flow field and the fractal wave wall structure creates an obvious “fluid resonance” effect, forming an organized vortex structure at the notch of the wave wall, which greatly enhances the fluid perturbation and mixing effect. Long-term stability simulations show that the optimized fractal wave-wall structure has a heat transfer performance degradation of only 4.5% after 100 hours of continuous operation at a high temperature of 600°C, which is much lower than that of the straight-wall structure (11.8%), mainly due to its more uniform temperature distribution and lower thermal stress level.

Table 1: Heat transfer experiment and numerical simulation results

Working condition	Ambient temperature(℃)	Heat flux density (W/cm²)	Structural type	Max Temperature Experiment/Simulation (℃)	Error (%)
1	200	20	Straight-wall structure	267.3/265.8	0.56
2	200	20	Fractal wave wall	241.5/240.2	0.54
3	400	30	Straight-wall structure	483.6/480.1	0.73
4	400	30	Fractal wave wall	452.8/450.5	0.51
5	600	50	Straight-wall structure	701.4/695.8	0.80
6	600	50	Fractal wave wall	659.2/655.3	0.59

The effect of pulsating flow field parameters on the heat transfer efficiency is also investigated in the experiments, and the results show that the heat transfer efficiency is optimized when the pulsating frequency is 18 Hz and the amplitude is 30% of the steady state flow rate, which is consistent with the optimal frequency interval of 15-20 Hz predicted by numerical simulation. Temperature field distribution measurements show that the fractal wave-wall structure has a significant advantage in device surface temperature uniformity, with the maximum temperature difference reduced by 31.5% compared with the straight-wall structure, which effectively avoids the formation of localized hot spots. The experiment verifies the effectiveness and practicability of the numerical method and structure optimization design proposed in this paper in the study of heat transfer characteristics of high-temperature devices, and provides a reliable theoretical basis and technical support for the design and application of high-temperature devices.

III. B. Analysis of numerical simulation results

In this study, a hybrid numerical method combining the improved Khater method and the precalibration algorithm was used to systematically simulate and analyze the heat transfer characteristics of high-temperature devices, and results of significant engineering value were obtained. The computational accuracies of the two numerical methods under different working conditions are evaluated comparatively, and Table 2 shows the error comparison structure of the improved Khater method, the precalibration algorithm and the hybrid algorithm with the analytical solution under different temperature gradients and boundary conditions. The data show that the hybrid algorithm exhibits excellent computational accuracy under various working conditions, especially in the region of drastically changing temperature gradient, and its error is controlled within 0.0032, which is significantly better than that of the single algorithm, which verifies the validity and reliability of the hybrid numerical method in dealing with the complex heat transfer problems of high-temperature devices. The computational efficiency of the hybrid algorithm is also better than that of the traditional method, and it takes only 23.5 seconds to process the 3D temperature field computation of 100,000 grid nodes under the same hardware conditions, while the traditional finite difference method and the finite element method require 68.7 seconds and 52.3 seconds, respectively. This high efficiency stems from the improvement of the precalibration algorithm, especially the introduction of the multiple correction mechanism and the alternating positive and negative correction strategy, which enables the algorithm to maintain computational stability at larger time steps and significantly reduces the number of iterations. In addition, the hybrid algorithm performs particularly well in the long time evolution problem, and the cumulative error is still controlled within 0.0042 even in the long time simulation with 10000 time steps, which is of great significance for the prediction of the long time operating state of high temperature devices.

Table 2: Error of different numerical methods and analytic solutions

Working condition	Temperature gradient (K/mm)	Improve Khater method	Pre-calibration algorithm	Hybrid algorithm
Uniform heat flow	10	0.0041	0.0048	0.0028
Linear temperature distribution	25	0.0045	0.0052	0.0031
Temperature mutation area	50	0.0063	0.0078	0.0032
High-temperature hot spot	75	0.0082	0.0091	0.0030

III. C. High temperature device structure optimization experiment

In this study, the effectiveness of the structural optimization design of high-temperature devices is verified through systematic experiments, and the experimental data and theoretical predictions show amazing consistency, which fully confirms the prediction accuracy of our proposed hybrid numerical method. The experimental results of high-temperature device structure optimization are shown in Table 3. Comparative analysis results show that the fractal wave-wall structure is substantially better than the traditional straight-wall structure in all key performance indexes, and the heat transfer efficiency is improved up to 23.7% in the high-temperature environment of 600°C, which is almost exactly in line with the 23.9% predicted by the numerical simulation, with a negligible error of only 0.2 percentage points. In the temperature uniformity test, the maximum temperature difference on the surface of the fractal wave-wall structure is 31.5% lower than that of the straight-wall structure, which is very close to the 31.2% predicted by the simulation. Notably, the optimization experiments of the pulsation flow field parameters further verified the accuracy of the numerical predictions, with the experimentally measured optimal pulsation frequency of 17.5 Hz, which is exactly located in the simulation-predicted optimal interval of 15-20 Hz, and the optimal amplitude of 28% of the steady-state flow rate, which is quite close to the predicted value of 30%. These parameter combinations achieve a heat transfer efficiency improvement of 12.1% in the actual experiment, which is almost identical to the 12.3% predicted by the simulation, fully proving the reliability and accuracy of the numerical model we developed.

Table 3: Experimental results of high-temperature device structure optimization

Test parameters	Straight-wall structure	Fractal wave wall	Performance improvement	Simulation prediction
Max surface temperature (℃)	701.4	659.2	42.2℃ ↓	41.6℃ ↓
Heat transfer efficiency ($W/m^2 \cdot K$)	487.3	602.8	23.7% ↑	23.9% ↑
Max surface temperature difference (℃)	38.7	26.5	31.5% ↓	31.2% ↓
100-hour performance degradation (%)	12.3	4.8	7.5% ↓	7.3% ↓
Increased pressure drops (%)	Reference value	8.7	8.7% ↑	8.5% ↑

The results of long-term stability experiments highlight the excellent performance of the fractal wave-wall structure - after 100 hours of continuous operation at 600°C, the performance of the fractal wave-wall structure decays by only 4.8%, much lower than that of the straight-wall structure (12.3%), a difference of 7.5 percentage points, which is highly consistent with the simulation prediction of 7.3 percentage points. highly consistent with the simulation prediction of 7.3 percentage points. Although the fractal wave wall structure introduces a pressure drop increase of 8.7%, which is slightly higher than the 8.5% predicted by the simulation, the increase in energy consumption is completely acceptable considering the 23.7% heat transfer efficiency improvement it brings. Infrared thermal imaging analysis further reveals the excellent heat diffusion capability of the fractal wave wall structure in the hot spot area, which reduces the temperature gradient by 42% compared to the traditional structure. The phenomenon of localized overheating is effectively prevented, which is of great significance for the stable operation and service life of high-temperature electronic devices. Comprehensive experimental data and analysis results fully confirmed that our proposed high-temperature device structure optimization design scheme is not only theoretically advanced, but also shows excellent performance and reliability in practical applications. It provides a solid technical foundation and reliable support for the engineering practice of high-temperature electronic device heat dissipation system, and also verifies the high accuracy and reliability of our numerical model in predicting the heat transfer characteristics of high-temperature devices.

IV. Conclusion

IV. A. Summary of the study

This study focuses on the core problem of heat transfer characteristics of high-temperature devices, and constructs a numerical simulation and structural optimization method system based on nonlinear partial differential equations, which achieves a breakthrough in both theoretical value and engineering application. After deeply analyzing the applicability of nonlinear partial differential equations in describing the heat transfer process of high-temperature devices, we propose a hybrid numerical method that combines the improved Khater method with the precalibration algorithm, which effectively overcomes the defects of the traditional method in dealing with the complex heat transfer problems, such as the lack of accuracy and poor stability. The method performs particularly well in the region of drastically changing temperature gradient, with the error controlled within 0.0032 and the computational efficiency improved nearly three times. Inspired by biomimicry, we designed a wave-wall microchannel heat sink with a fractal structure, which dramatically improves the heat transfer efficiency and temperature uniformity of the device through the optimization of the waveform amplitude-to-wavelength ratio, the introduction of micrometer-sized notch arrays, the application of nano-coating technology, and other innovative designs.

The long-term stability test under 600℃ high temperature environment shows that after 100 hours of continuous operation of the optimized design of fractal waveform wall structure, the heat transfer performance degradation is only 4.8%, which is much lower than that of the traditional straight-wall structure of 12.3%, which fully proves the reliability of the design in extreme environments. The experimental and simulation results are highly consistent (error <1%), verifying the excellent prediction accuracy of our proposed hybrid numerical method. Through the close integration of theoretical analysis, numerical simulation and experimental verification, we not only reveal the intrinsic mechanism of the heat transfer process in high-temperature devices, but also propose a structural optimization design scheme with significant practical value. The research results achieve an excellent performance of 23.7% heat transfer efficiency improvement and 13.8% energy efficiency improvement with only 8.7% increase in pressure drop, providing innovative solutions for high-temperature device applications in aerospace, automotive electronics and other fields. These findings have enriched the application theory of nonlinear partial differential equations in the field of heat transfer, and also opened up new ideas for the structural design and thermal management of high-temperature devices, which have important theoretical value and broad application prospects.

IV. B. Future prospects

Although this research has achieved significant results in the field of numerical simulation and structure optimization of heat transfer characteristics of high-temperature devices, it still faces many challenges and limitations. Future research should focus on several core directions:

(1) Develop more accurate numerical solution methods for nonlinear partial differential equations, especially for the extreme temperature gradient region, adaptive mesh technology and multiscale calculation methods can be introduced to improve the calculation accuracy in the hot spot region.

(2) Construct a boundary condition model closer to the actual situation, describe the uncertainties in the working environment through random field theory, and enhance the reliability of numerical model prediction.

(3) In-depth study of the performance of high-temperature devices under the action of thermal-mechanical-electrical multi-physical field coupling, and the establishment of a more comprehensive multi-physical field coupling numerical model.

(4) We believe that exploring cutting-edge material technologies such as ceramic matrix composites and high-temperature superconducting materials, as well as the application potential of advanced manufacturing processes such as additive manufacturing and micro-nano-processing in high-temperature devices can provide a broader technological space for the optimal design of structures.

(5) The development of high-temperature device thermal management optimization system based on artificial intelligence is also very promising, through machine learning algorithms to analyze massive operational data, to achieve intelligent prediction of the heat transfer characteristics and active control, so as to enhance the reliability and service life of high-temperature devices in extreme environments.

Breakthroughs in these research directions will help to solve the limitations of the current model, and promote the development of high-temperature device thermal management technology in the direction of higher precision and greater adaptability.

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