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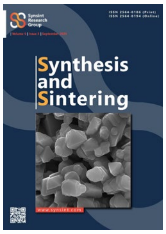

Review article

Numerical insights into thermal behavior of advanced ceramics using COMSOL Multiphysics: A mini review

Takunda Happison Nyenyewa

Department of Mechanical Engineering, University of Kyrenia, Kyrenia, Cyprus

ABSTRACT

This paper provides an in-depth overview of heat transfer in advanced ceramics using COMSOL Multiphysics, aiming to achieve accurate simulations and analytical insights for ultra-high-temperature ceramics (UHTCs). COMSOL Multiphysics has applications across various industries that require advanced investigations into the performance of materials under extreme heat conditions. The finite element method (FEM) implemented in the software serves as an effective tool for solving governing equations and addressing heat transfer problems in a wide range of cutting-edge applications. The focus is not only on current methodological approaches but also on the future evolution of thermal behavior analysis in ceramics, such as the integration of machine learning. Overall, the results highlight the importance of numerical methods as a bridge between materials science and high-level engineering applications.

KEYWORDS

COMSOL Multiphysics
Advanced ceramics
Heat transfer
Numerical simulation
Thermal analysis
Finite element method

1. Introduction

Advanced ceramics have made significant progress in high-temperature applications due to their chemical stability, mechanical strength, and thermal conductivity. These materials serve as the cornerstone for applications such as aerospace thermal insulation, biomedical implants, energy devices, and electronic packaging, where their hardness and corrosion resistance enable improved performance under mechanical stress and extreme heat conditions [1]. It is essential to develop a comprehensive understanding of how heat transfer influences these ceramics when evaluating thermal efficiency, optimizing process operations, and preventing premature material failure. Nonetheless, their complex thermophysical responses, particularly under high heating rates, localized stresses, or non-uniform thermal conditions, pose significant challenges to achieving optimal design and performance. Therefore, researchers increasingly employ numerical tools such as COMSOL Multiphysics and MATLAB to model and predict the thermal behavior of ceramics during production [2].

The use of numerical techniques has become a crucial complement to experimental studies, driven by finite element methods and the ongoing evolution toward predictive, data-driven materials science. These computer simulations enable detailed examinations of laser–material interactions [3], the thermal resistance of composite coatings [4], and microstructural development during sintering [5]. By reducing dependence on experimental trial and error, computational techniques streamline the optimization of ceramic production. COMSOL Multiphysics is particularly valuable due to its ability to model interdependent phenomena such as heat conduction, radiation, fluid flow, and electromagnetic fields simultaneously, making it well-suited for high-accuracy applications like solar thermal receivers [6] and neutron–thermal interaction systems [7].

The growing complexity of part geometries and functionalities is increasingly shaping modern ceramic processing. Emerging techniques such as additive manufacturing and spark plasma sintering now enable the fabrication of structures with intricate, real-time thermal characteristics that can be accurately reproduced in silico [8, 9]. For instance, laser powder bed fusion produces complex ternary eutectic ceramics that require precise thermal management to prevent defects such as cracking or irregular densification [8]. Similarly, simulations of

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* Corresponding author. *E-mail address:* k20221488@std.kyrenia.edu.tr (T.H. Nyenyewa)

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sample and die geometries in spark plasma sintering enable optimization of heat transfer and final product quality [10]. These advances position numerical simulation not merely as a verification tool but as an integral component of ceramic process design.

This article integrates experimental approaches with COMSOL-based modeling to investigate heat transfer in advanced ceramics. Five key application areas are discussed: laser processing and additive manufacturing, energy technology, cutting tools, sintering behavior, and gas turbine-related technology. Critical issues concerning thermal characterization, along with the growing importance of computational methods in the design of high-performance ceramics, are also addressed. Through this review, we aim to identify common trends and propose future research directions in ceramic development supported by numerical simulation.

2. Laser processing and additive manufacturing

Laser-assisted machining (LAM) has been demonstrated as an effective technique for processing hard and brittle materials by preheating the workpiece with a high-intensity laser beam, thereby reducing cutting forces and improving machinability [3]. COMSOL Multiphysics simulations provide detailed analyses of the temperature distribution in LAM, enabling the optimization of process parameters to enhance thermal efficiency and surface integrity [3]. Among additive manufacturing techniques, laser powder bed fusion (LPBF) shows great potential for fabricating complex ternary eutectic ceramics, but it is prone to thermally induced cracking due to steep thermal gradients [8]. Finite element modeling and COMSOL simulations enable the study of crack propagation by analyzing stress and temperature fields under varying manufacturing conditions [8]. Similarly, laser ablation of alumina ceramics is effectively studied through combined experimental and numerical approaches using COMSOL-based models, which accurately predict transient thermal fields and crack growth behavior, guiding the optimization of laser parameters to achieve uniform surface quality over large areas [11].

Two-dimensional simulations of laser drilling in AlON ceramics demonstrate the dominant influence of defocus distance on ablation depth, material removal rate, and machining quality [12]. Additionally, laser cladding of Al_2O_3/SiC composites assisted by microwaves has been simulated in COMSOL to investigate thermal residual stresses and the effects of key parameters, such as scanning velocity and laser power, on stress development and heat flow patterns [2]. Together, these studies underscore the fundamental role of numerical modeling, particularly using COMSOL Multiphysics, in enhancing the accuracy, reliability, and scalability of laser-based fabrication processes for advanced ceramics.

Fan et al. [3] investigated laser-assisted machining of glass-ceramic materials, focusing on the impact of accurate thermal property measurements and numerical simulations on process improvement. Temperature distribution simulations were performed in COMSOL Multiphysics, using measured emissivity ($\varepsilon = 0.62$) and absorptivity ($\alpha = 0.68$) as key factors governing heat absorption and dissipation. The analysis showed that higher laser power and larger spot radii enhance heating efficiency, while lower workpiece speeds result in higher temperatures due to prolonged exposure. Simulation predictions closely matched experimental results, validating the COMSOL model as an essential tool for optimizing LAM parameters and minimizing thermal damage.

Li and Zhou [2] investigated microwave heating of Al_2O_3/SiC composites in a multimode cavity to enhance thermal efficiency and uniformity using COMSOL Multiphysics. A 3D finite element model coupling electromagnetic and thermal physics was employed to simulate electric field distributions and temperature rise. The study examined the effects of microwave power, sample geometry, and crucible material, providing valuable insights for scale-up optimization. Simulation results agreed with experimental measurements within an error of less than 2%, validating the model. Additionally, COMSOL's integrated electromagnetic and thermophysical modules simplified the setup and analysis.

Shen et al. [8] investigated complex-structured ternary eutectic ceramics fabricated via laser powder bed fusion (LPBF), an additive manufacturing process for high-performance ceramic components. The study employed COMSOL Multiphysics to predict temperature fields and residual stresses during LPBF, taking into account the ceramic's high melting point and fatigue behavior. In this process, laser energy fuses ceramic powders layer by layer, with eutectic composites enhancing mechanical and thermal properties. COMSOL simulations captured thermal gradients, phase transformations, and stress distributions, while key process parameters—such as laser power, scan speed, and layer thickness—were controlled. This modeling approach enabled the minimization of defects, including thermal cracking and distortion, thereby improving structural integrity and fabrication quality.

3. Energy applications

COMSOL Multiphysics has become an essential tool for optimizing heat transfer in energy systems, particularly in solar thermal receivers and fuel applications. Porous ceramic volumetric absorbers play a critical role in maximizing energy collection through volumetric heating in solar reactors. Experimental studies have shown that increasing pore density enhances surface absorption and heat generation, but also increases thermal gradients, whereas higher airflow rates can reduce these gradients by promoting convective cooling [6]. In solar receivers with porous media at elevated temperatures, volumetric convection dominates heat transfer, and key parameters such as concentration ratio and air velocity strongly influence thermal efficiency [13]. To further optimize design, deep neural networks have been integrated with COMSOL simulations, enabling high-throughput predictions of critical parameters such as outlet temperature, pressure drop, and mechanical reliability, thereby ensuring absorber efficiency and safety under operational loads [14]. In some applications, COMSOL has also been successfully coupled with Monte Carlo simulations to model fully ceramic microencapsulated (FCM) fuels. This combined approach allows accurate analysis of power density, heat distribution, and thermal neutron self-shielding effects, supporting the thermal-hydraulic design of next-generation fuel systems [7]. Collectively, these studies demonstrate the capability of simulation-based design to develop more efficient, safer, and higher-capacity energy technologies.

Arreola-Ramos et al. [6] experimentally investigated the thermal efficiency of partially stabilized zirconia (PSZ) ceramic foams as volumetric solar energy absorbers. By combining experimental tests with COMSOL Multiphysics simulations, the study provides a robust framework for analyzing and optimizing absorber design (See Figs. 1–4).

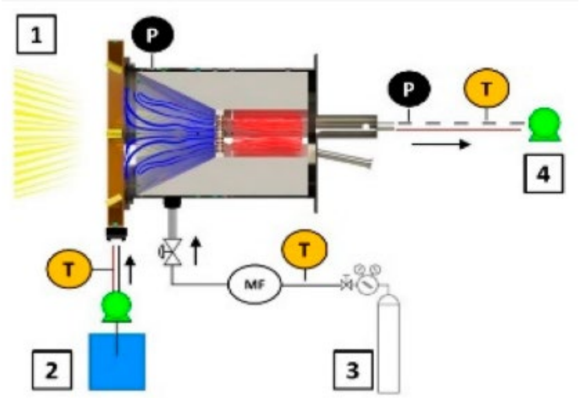

Fig. 1. Solar reactor operation diagram showing the temperature (T) and pressure (P) sensors, the mass flow controllers (MF), and the gas inlet/outlet, also illustrates (1) the incoming radiation flux, (2) the water reservoir, (3) the compressed air tank, and (4) the air extractor. Reprinted from Ref. [6].

Ceramic foam samples with different pore densities were compared under varying airflow rates and radiative power inputs in a solar furnace. Experimental temperature measurements were used to inform numerical simulations in COMSOL Multiphysics 5.2. The model calculated thermal conductivity, convection, radiation, and the volumetric heat transfer coefficient by fitting simulation data to the thermocouple measurements.

This two-step process enabled the development of a selection metric for highly effective volumetric absorbers based on structural and thermal material properties. The study demonstrates how simulation-supported analysis can be applied to improve absorber performance in solar energy systems.

Yang et al. [13] simulated heat transfer in a 50-MW$_{th}$ beam-down concentrating solar thermal system with a ceramic foam volumetric receiver using COMSOL Multiphysics 6.1. The simulation incorporated coupled radiative, convective, and conductive mechanisms under realistic operating conditions to analyze thermal behavior, energy losses, and performance enhancement. The ceramic foam receiver effectively absorbed solar radiation, transferring heat volumetrically to the working fluid. Loss analysis quantified optical (33%), re-radiation (20%), convective (6%), and conductive (1%) losses. Despite these losses, the system achieved a high exit air temperature of 1441 K, with solar-to-thermal and solar-to-exergy efficiencies of 39% and 31%, respectively. COMSOL simulations indicated that increasing airflow and concentration ratio significantly improve efficiency, while porosity and thermal conductivity have a smaller impact. The study demonstrates the effectiveness of COMSOL in designing optimized solar thermal receivers using advanced ceramics.

Sharma et al. [14] designed porous volumetric solar receivers (PVSRs) using silicon carbide (SiC) ceramics by integrating COMSOL Multiphysics simulations with deep neural networks (DNNs). A high-fidelity thermal–structural model in COMSOL was developed to simulate radiative, convective, and conductive heat transfer across a wide range of porosity and solar flux conditions. SiC was chosen for its high thermal resistance, mechanical strength, and low thermal expansion.

COMSOL simulation data were used to train a deep neural network capable of predicting temperature profiles, thermal performance, and mechanical stress at reduced computational cost. By using the DNN to

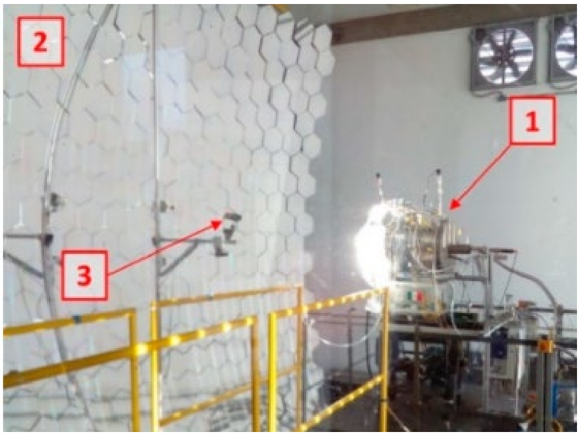

Fig. 2. The solar reactor installed in the high radiative flux solar furnace (HoSIER), (1) the reactor, (2) solar concentrator panel, and (3) front pyrometer. Reprinted from Ref. [6].

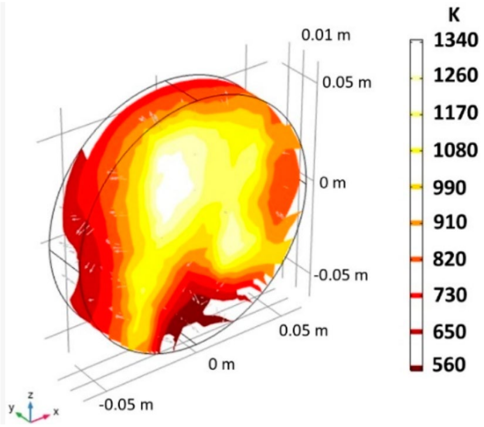

Fig. 3. Isothermal surfaces corresponding to the 20 PPI absorber obtained from numerical simulations. Reprinted from Ref. [6].

optimize parameters such as solar flux, porosity, and airflow rate, thermal performance, mechanical safety, and high operational efficiency were achieved simultaneously. This hybrid approach demonstrates how advanced ceramics combined with AI-based modeling can enhance reliability and inform the design of next-generation solar thermal systems [14].

Weng et al. [7] employed Monte Carlo simulations in combination with COMSOL Multiphysics to perform coupled neutronics and thermohydraulic analyses of a reactor. Heat transfer in advanced ceramic materials such as silicon carbide, which are critical components of fuel systems, was simulated using COMSOL. The Monte Carlo method was applied to neutron transport calculations, including energy deposition and fission rate determination within the reactor core, while COMSOL performed thermohydraulic simulations encompassing heat conduction, convection, and radiation within reactor components.

The combined use of Monte Carlo and COMSOL simulations enables accurate prediction of heating and thermal responses in reactor components. The study investigates SiC as fuel cladding for its high thermal conductivity, strength, and radiation resistance. The simulations account for coolant flow, heat transfer within the reactor core, fluid–structure interaction, and temperature-dependent material properties. By integrating both methods, the study provides a comprehensive understanding of heating, fuel performance, and safety margins. This approach enhances the design and optimization of high-temperature gas-cooled reactors (HTGRs) and molten salt reactors (MSRs), emphasizing the role of advanced ceramics in improving reactor efficiency, lifetime, and safety. Such research is essential for the development of next-generation reactors with superior performance and safety features [7].

4. Cutting tools and wear resistance

High-performance cutting tools are used for advanced ceramics to enhance heat resistance, toughness, and machining efficiency. COMSOL Multiphysics has been extensively applied to investigate the thermal behavior of coated cutting tools in industrial turning operations, aiming to reduce tool wear and extend tool life [4]. Transient heat transfer simulations, incorporating thermal contact resistance at the tool–holder interface, show that coated tools experience significantly lower temperature increases compared to uncoated tools, particularly when optimized coatings are applied [4].

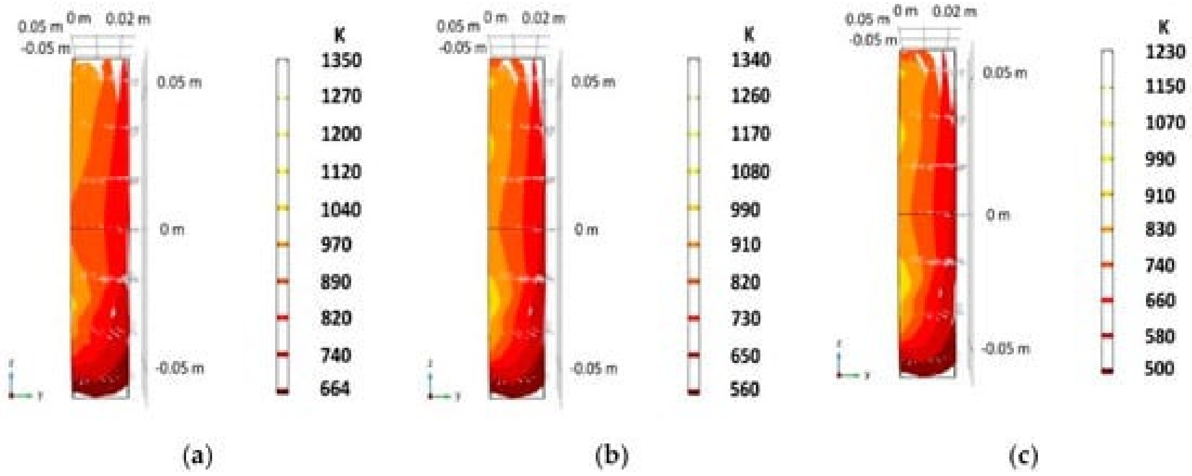

Fig. 4. Isothermal surfaces on the z-y plane (perpendicular to thickness) of the absorber material. a) 10 PPI, b) 20 PPI, and c) 30 PPI. Reprinted from Ref. [6].

Composite ceramics such as TiB_2–SiC and TiB_2–SiC–GNP have also been studied due to their improved heat transfer, structural properties under extreme thermal conditions, and potential applications in both machining and high-performance heat exchanger systems [15]. Furthermore, integrating finite element (FE) simulations with machine learning (ML) techniques has enabled the optimization of ceramic geometries under thermal shock, successfully identifying material configurations that minimize deformation while maximizing heat absorption under aggressive cutting conditions [16].

Fernandes Brito et al. [4] conducted a detailed analysis of the thermal behavior of cemented carbide cutting tools using COMSOL Multiphysics, with particular focus on the effects of ceramic coatings and thermal contact resistance. The study evaluated the impact of multilayer coatings: titanium nitride (TiN), aluminum oxide (Al_2O_3), and titanium carbonitride (TiCN) on heat dissipation and thermal gradients during machining. Three-dimensional COMSOL modeling was employed to simulate transient heat transfer phenomena, including conduction, convection, and radiation, along with temperature-dependent thermal contact resistance and material properties at the tool–holder interface. The results indicate that coated tools experience the smallest temperature increases compared to uncoated tools, particularly when thermal contact resistance is considered. Optimizing coating combinations and film thicknesses was shown to enhance heat transfer, minimize thermal stress, and extend tool life. This coupled simulation approach establishes ceramic coatings as a benchmark for improving machining efficiency and wear resistance in high-temperature cutting processes (See Figs. 5 and 6).

Nekahi et al. [15] conducted a thermal performance simulation of TiB_2–SiC–graphene nanoplatelet (GNP) composite finned heat exchangers using COMSOL Multiphysics under elevated temperature conditions. By combining the high thermal conductivity of graphene with the mechanical strength of TiB_2 and SiC, the study provides insights into heat dissipation and mechanical stability at high temperatures. The simulation accounted for conduction, convection, and fluid heat flow, achieving improved temperature uniformity and reduced thermal resistance. The composite heat exchangers demonstrated up to 8.2% higher efficiency compared to conventional Al_2O_3-based exchangers. Notably, a 15% reduction in exchanger length without performance loss led to a 6.7% improvement in overall efficiency and material savings, highlighting the potential of these composites in compact, high-performance thermal systems.

Ravanbakhsh et al. [16] investigated the thermomechanical behavior of interlocking ceramics using a hybrid finite element analysis (FEA) and machine learning approach to enhance structural integrity under thermal shock. COMSOL Multiphysics was employed to simulate stress distribution, crack propagation, and heat conduction in ceramics composed of SiC and Al_2O_3, selected for their high thermal stability and strength. The interlocking structures improve load distribution and toughness by dissipating energy through controlled fracturing under thermal stress. Machine learning algorithms, trained on FEA simulation results, were used to predict and optimize design parameters such as geometry, interfacial angles, and contact surface areas, significantly reducing computational cost while maintaining accuracy. The study demonstrates that interlocking geometries effectively reduce thermal strain concentrations and slow crack propagation, making these ceramics promising candidates for heat shields, wear-resistant coatings, and load-bearing thermal barriers.

5. Sintering and microstructure control

Sintering is a high-temperature heat treatment process in which powder particles are consolidated into a dense solid state without melting. The technique relies on atomic diffusion to close pores and harden the material, enhancing thermal conductivity. However, high-temperature ceramics such as silicon carbide, tungsten carbide (WC), and titanium carbide (TiC) present challenges due to low self-diffusivity and strong covalent bonding, which hinder full densification and uniform grain growth. To address these limitations, advanced methods such as spark plasma sintering (SPS) and pulsed electric pressure are employed, enabling rapid densification at lower temperatures with better control over porosity and grain size [5]. COMSOL Multiphysics simulations are used to investigate and optimize sintering processes by accurately assessing heat distribution, thermal gradients, densification kinetics, and stress formation.

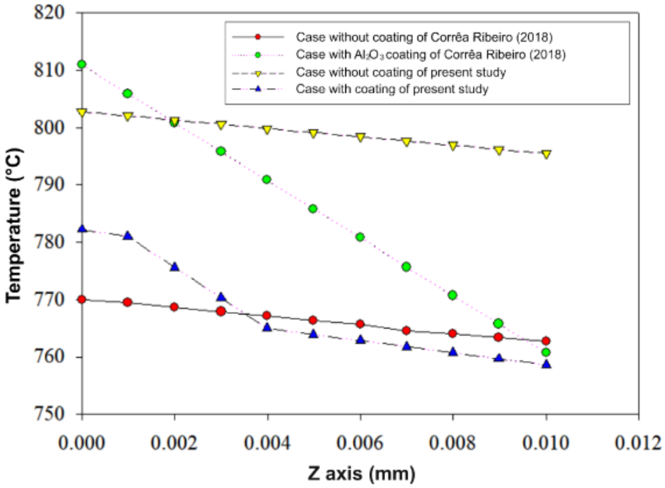

Fig. 5. Comparison of temperatures in the coating, calculated in numerical probes, for t = 57 s, between this work and the work of comparison of temperatures in the coating, calculated in numerical probes, for t = 57 s, between this work and the work of Correa Ribeiro (2018). Reprinted from Ref. [4]. License Link https://creativecommons.org/licenses/by/4.0/.

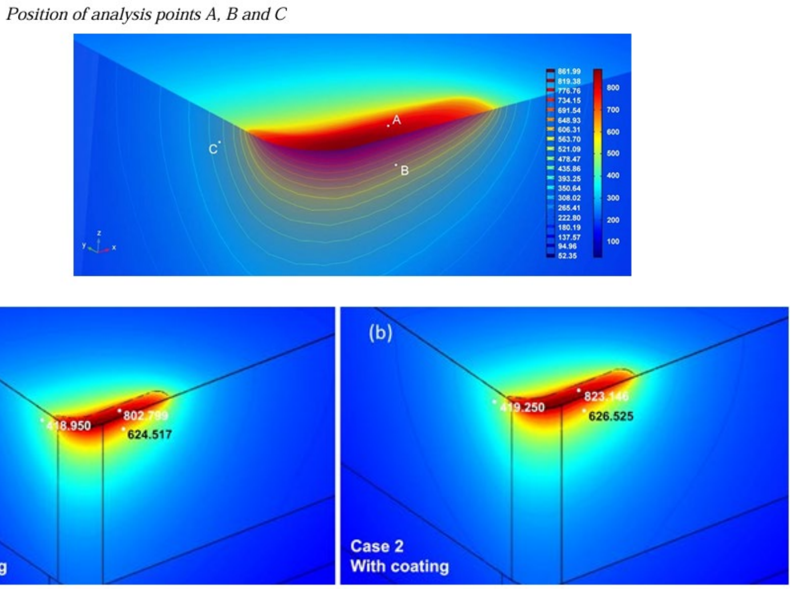

Fig. 6. Temperature fields and temperatures of the three points between cases 1 and 2 at time t =57 s. Reprinted from Ref. [4]. License Link https://creativecommons.org/licenses/by/4.0/.

For example, numerical simulations of porous SiC indicate that increased porosity raises core temperatures while reducing thermal gradients, thereby degrading structural uniformity [9]. Similarly, simulations of WC and TiC sintering highlight the dominant influence of geometric factors such as die shape and sample size on thermal uniformity and densification efficiency [10]. Integrating computational and experimental approaches enables researchers to maximize microstructural control, prevent defects, and fabricate high-performance ceramics for demanding applications in aerospace, defense, and energy technologies.

Lei et al. [5] conducted a numerical study of heat transfer mechanisms during spark plasma sintering of porous silicon carbide using COMSOL Multiphysics. Due to the strong covalent bonding in SiC, conventional sintering is insufficient for densification, making SPS - employing uniaxial pressure and pulsed electric currents- a preferred method. The study used porous SiC cylindrical samples with varying porosity to investigate their effects on thermal and electrical properties during sintering. COMSOL simulations modeled coupled heat conduction, Joule heating, and radiative heat transfer within the porous samples. Results showed that the maximum temperature and current density occur at the punch/spacer interface, and that the central sample temperature increases with porosity, ranging from approximately 1960 °C at 1% porosity to 2010 °C at 60% porosity.

Higher porosity, which increases temperature gradients between the sample center and edges, leads to non-uniform heat distribution. This non-uniformity adversely affects microstructure development and densification behavior, resulting in elevated internal stresses and heterogeneous mechanical properties. The study also addresses the dynamic thermal and electrical conductivity of SiC during sintering and their impact on heat transfer efficiency. Simulations incorporating high-fidelity porosity–heat transfer models and SPS conditions can guide the optimization of sintering parameters, aiming to achieve homogeneous densification and improved mechanical performance of porous SiC components for high-temperature applications. The governing equations used in the simulations include the thermal diffusion equation, convective heat transfer of water, and the Stefan-Boltzmann law.

Grippi et al. [9] investigated the combination of additive manufacturing (AM) and spark plasma sintering for fabricating tungsten carbide components with complex geometries at reduced pressures and temperatures. Using COMSOL Multiphysics, the study modeled sintering parameters through computational simulations of temperature distribution, electric field, and the densification process. Simulation results demonstrated the influence of Joule heating, thermal conduction, and radiative transfer on porosity and temperature gradient development during SPS. This low-energy approach not only provides precise control over microstructure formation but also limits grain growth while achieving full density and maintaining mechanical integrity. The study confirms the effectiveness of AM-assisted SPS for producing high-performance WC ceramics suitable for wear-resistant and cutting tool applications, with COMSOL facilitating the analysis of processing–microstructure relationships.

Bagheri et al. [10] conducted a comprehensive numerical study on sample and die geometries to optimize temperature distribution during spark plasma sintering of TiC ceramics. COMSOL Multiphysics was used to model electric field distribution, heat transfer, and densification behavior to improve thermal efficiency in the SPS process. Titanium carbide, being hard, thermally stable, and wear-resistant, requires precise thermal control to achieve full densification and superior mechanical properties. The study highlights the influence of die wall thickness, sample-to-die contact area, and electrode positioning on Joule heating and temperature uniformity. Results indicate that optimized configurations significantly reduce thermal losses, ensuring uniform heating, decreased porosity, and enhanced grain bonding. By optimizing die and sample geometries, the study presents an effective approach to improving sintering performance and facilitating the production of high-performance TiC ceramics for cutting tools and structural applications.

6. Turbine blades and hypersonic systems

UHTCs are increasingly used in turbine blades and hypersonic systems due to their ability to withstand extreme thermal and mechanical loads. Composites such as HfB_2–SiC offer enhanced ablation resistance and thermal protection, making them suitable for advanced aerospace structures. Lyu et al. [1] synthesized HfB_2–SiC from precursor liquids, demonstrating its structural stability at high temperatures and its potential as a lightweight thermal barrier material for hypersonic flight [1]. In parallel, Zabihi et al. [17] developed a non-contact damage detection method for wind turbine blades using laser doppler vibrometers (LDVs) to identify early-stage cracks based on changes in vibration behavior, crucial for maintaining the integrity of ceramic-coated blades under cyclic thermal loading [17]. Zhao et al. [18] investigated the film-cooling performance of preformed-hole 2.5D braided ceramic matrix composite (CMC) plates using COMSOL Multiphysics to simulate high-speed thermal conditions, highlighting the importance of geometric design in optimizing surface cooling for long-term turbine component survivability [18]. Together, these studies underscore the pivotal role of UHTCs and simulation-driven design in enhancing the reliability and performance of aerospace systems exposed to ultra-high thermal fluxes.

In the pursuit of high-performance aerostructure materials, Lyu et al. [1] investigated HfB_2–SiC composites synthesized from a liquid SiHfCB precursor to achieve ablation resistance and mechanical uniformity at ultra-high temperatures. The resulting materials exhibited enhanced thermal stability, structural integrity, and heat dissipation, making them well-suited for turbine blades and thermal protection in hypersonic vehicles. COMSOL Multiphysics simulations further optimized performance by modeling heat transfer and ablation behavior, supporting applications at temperatures exceeding 2000 °C.

Although not focused on ceramics, Zabihi et al. [17] present an engaging structural health monitoring technique using LDVs, which could be adapted for non-destructive testing of turbine blades and other high-temperature components. By detecting vibrational irregularities associated with structural damage, this method complements COMSOL-based modeling, providing a comprehensive strategy to investigate damage initiation and propagation in aerospace-grade ceramics subjected to mechanical and thermal loads.

Zhao et al. [18] numerically investigated the film-cooling performance of 2.5D braided CMC pre-drilled hole plates using COMSOL Multiphysics 5.4 for high-temperature aerospace applications, such as turbine blades. Four-hole designs were compared: extruded (EP-Hole), woven (WP-Hole), and two drilled variants (DP-Hole1 and DP-Hole2). The results showed that pre-existing voids introduced during braiding reduced thermal gradients by up to 123.3% compared to drilled holes, enhancing both cooling performance and structural strength. The study also reported an increase in the anisotropic thermal conductivity ratio (Kr) from 3.32 to 13.05, leading to a ~10% decrease in hot-wall cooling efficiency, highlighting the limitations imposed by material orientation in thermal design. These findings are critical for optimizing both structural configuration and cooling performance in CMC aerospace components.

7. Challenges and future directions

7.1. Challenges

- **Multicomponent Multiphysics coupling in ceramic matrix composites**

Next-generation ceramics, particularly ceramic matrix composites, undergo complex processing routes such as reactive melt infiltration (RMI) and chemical vapor infusion (CVI). These processes involve multiple interrelated phenomena, including porous media fluid flow, capillary action, chemical reactions, phase transformations, and residual stress development. Modeling such coupled processes in COMSOL requires the integration of various physics interfaces, such as heat transfer, fluid dynamics, and chemical kinetics, into a unified framework. However, this Multiphysics coupling is often computationally demanding and challenging to stabilize. Accurate representation of these interactions is essential for predictive modeling of material behavior during CMC manufacturing.

- **Simulation of porous media and thermal coupling constraints**

Modeling heat transfer in porous ceramics presents several challenges, particularly in defining appropriate boundary conditions and achieving effective thermal coupling between porous regions and adjacent solid or fluid domains. COMSOL users have reported difficulties in establishing these thermal connections, especially when dealing with complex geometries or imported models. Such limitations can result in inaccurate temperature distribution predictions and often necessitate advanced modeling strategies to ensure reliable simulation outcomes [19].

- **Computational requirements and simulation output verification**

High-accuracy ceramic heat transfer simulations often entail substantial computational demands, particularly when incorporating detailed microstructural features or transient analyses. Verifying simulation outputs against experimental results is essential to ensure model reliability; however, obtaining experimental validation data is challenging due to the multistage complexity and extreme temperatures involved in ceramic processing. Even when COMSOL provides accurate predictions, observed discrepancies between simulations and experiments highlight the critical importance of careful model calibration and validation [20].

7.2. Future direction

- **Multiphysics modeling interfacing with novel manufacturing technologies**

Integrating COMSOL Multiphysics with emerging manufacturing techniques such as additive manufacturing and spark plasma sintering has become increasingly important. Sakkaki et al. [21] investigated the SPS geometry of ZrB_2 ceramics using COMSOL and found that sample diameter significantly influences peak temperatures, thereby improving sintering efficiency. Similarly, multiscale modeling approaches that combine 1D and 3D simulations have enabled the design of advanced lattice-type ceramic heat exchangers, achieving optimal performance under high-temperature conditions.

- **Improved simulation reliability through experimental validation and machine learning**

A 2024 study experimentally validated a continuous conjugate heat transfer model using experimental data, achieving an average relative error of 7.35% in pressure drop and 0.38–1.5% in temperature distribution predictions. Additionally, the integration of machine learning with COMSOL simulations has gained increasing attention. Mohamed et al. [22] compared COMSOL-based models with artificial neural networks (ANNs) for predicting the Nusselt number in nanofluid heat transfer and found that, while COMSOL provided accurate results, certain neural network models outperformed it in specific applications.

- **Heat transfer mechanisms and materials**

Recent advances in heat transfer methods, such as flow-induced vibration in porous ceramic heat exchangers, have shown significant improvements in thermal performance. One experiment demonstrated that inducing vibration in a porous ceramic exchanger enhanced heat and mass transfer rates, reducing the time required to reach thermal equilibrium by up to 75% compared to non-vibrating systems. Additionally, the conceptual design of gas-gas ceramic compact heat exchangers for high-temperature applications has been investigated, with simulations optimizing parameters such as channel count and lattice layering to maximize thermal effectiveness [23, 24].

8. Conclusions

This review comprehensively examined the progress made between 2021 and 2026 in simulating the thermal behaviour of advanced ceramics using COMSOL Multiphysics. Finite element modelling has played a pivotal role across diverse applications from cutting tools and turbine blades to sintering optimization and hypersonic vehicles by predicting heat transfer mechanisms, thermal stresses, and densification characteristics under extreme conditions. COMSOL Multiphysics has empowered researchers to design and optimize processing routes, enhance microstructural control, and tailor the properties of ultra-high-temperature ceramics for aerospace and industrial use.

Beyond summarizing key findings, this review also addressed current challenges, including complex Multiphysics coupling, limited material property data at ultra-high temperatures, and computational inefficiencies. Emerging trends highlight the integration of Multiphysics simulations with machine learning, digital twins, and experimental validation, fostering the development of more accurate and predictive material models. The synergy between numerical simulations and experimental data will continue to drive innovation in next-generation ceramic systems, ensuring superior reliability, thermal performance, and structural integrity in the most demanding environments.

CRediT authorship contribution statement

Takunda Happison Nyenyewa: Writing – original draft, Writing – review & editing.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

Declaration of competing interest

The author declares no competing interests.

Declaration of AI use

This manuscript was linguistically reviewed and edited for grammar, clarity, and academic style with the assistance of ChatGPT (GPT-5, OpenAI).

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