Journal of Ceramic Processing Research. Vol. 26, No. 1, pp. 134~138 (2025)
(Received 22 December 2024, Received in revised form 2 February 2025, Accepted 5 February 2025)
https://doi.org/10.36410/jcpr.2025.26.1.134

JOURNAL OF
Ceramic
Processing Research

Finite element analysis of transient thermal response in a zirconia rack plate under applied heat flux and convective cooling

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This study presents a finite element analysis (FEA) of the transient thermal response of a zirconia rack plate subjected to an applied surface heat flux of 5000 W/m² and convective cooling with a heat transfer coefficient of 10 W/(K·m²). The transient temperature evolution was analyzed over a 100s simulation period to determine thermal behavior of the system before reaching steady-state conditions. The results indicate that at t = 10s, temperatures at different locations ranged from 297.8 K to 303.35 K, demonstrating the initial heat absorption phase. By t = 50s, the maximum temperature increased to 311.5 K, while at t = 100s, it reached 318.1 K, approaching thermal equilibrium. The temperature rise slowed down after 70s, suggesting a transition towards steady-state. The spatial temperature distribution showed that regions near the heat flux source exhibited higher temperatures, while areas near perforations experienced localized cooling, with temperature drops of up to ~20 K. The study also compared transient results with steady-state conditions, revealing that steady-state peak temperatures were significantly higher (452.3 K) and required additional time to be fully reached. These findings provide insights into the thermal performance of zirconia ceramics, contributing to their application in high-temperature environments where thermal management and equilibrium time are critical factors.

Keywords: Finite element analysis, Zirconia, Transient.

Introduction

Zirconia (ZrO_2) is extensively used in high-temperature applications due to its exceptional thermal stability, low thermal conductivity, and high resistance to thermal shock. These properties make ZrO_2 an ideal candidate for components exposed to extreme thermal environments, such as turbine blades, furnace linings, and structural plates used in industrial processes [1-5]. Unlike metallic components, which may suffer from thermal expansion and oxidation at elevated temperatures, ZrO_2 maintains its mechanical integrity and ensures prolonged operational stability.

Thermal management plays a crucial role in industrial and engineering applications, particularly in systems where heat dissipation efficiency directly impacts performance and durability. Heat exchangers, for instance, are integral components in cooling systems and power cycles due to their enhanced heat transfer capabilities, optimized contact surface area, and high heat transfer coefficients [6]. Various models and standards are employed to fabricate efficient heat exchange media, depending on the application requirements, type of coolant, cooling rate, and heat transfer demands. In surface cooling technology, liquid blocks and heat sinks are among the leading types of heat exchangers capable of dissipating significant thermal loads within compact spaces [7]. These technologies are commonly utilized in applications such as central processing unit (CPU) cooling, where forced convective fans enhance heat dissipation in a noiseless and efficient manner. However, traditional cooling methods utilizing air and conventional coolants have reached their performance limitations, necessitating the exploration of advanced materials and design approaches to improve heat transfer efficiency [8].

Structural components like rack plates, which are exposed to fluctuating thermal conditions, require thorough thermal analysis to ensure long-term performance and reliability. Variations in heat flux can introduce significant thermal stresses, leading to material degradation, warping, or even failure over extended periods [9]. Consequently, understanding the heat transfer characteristics of ZrO_2-based rack plates is essential for optimizing their design and ensuring their durability in high-temperature environments [10].

This study aims to evaluate both steady-state and transient heat transfer behavior of a ZrO_2 rack plate using

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Finite Element Analysis (FEA). The steady-state analysis provides insights into the temperature distribution under constant thermal conditions, while the transient analysis examines the time-dependent thermal response of the material [11]. By implementing realistic boundary conditions, this research contributes to the advancement of thermally efficient and structurally robust ZrO_2 components for high-performance applications. The results of this study can provide a foundation for the future design and optimization of ZrO_2-based components subjected to dynamic thermal conditions [12].

FEA Analysis

The methodology for the study of transient heat transfer in ZrO_2 material on a rack plate using FEA analysis involves conducting both Transient Heat Transfer Analysis and Steady-State Heat Transfer Analysis in *SimScale*. The transient heat transfer analysis is performed with a simulation interval of 100 seconds and a time step length of 10 seconds, capturing the time-dependent temperature changes. The boundary conditions for the analysis include a surface heat flux of 5000 W/m² to simulate thermal energy input, along with convective heat flux. The reference temperature (T_0) is maintained at 20 °C, and the heat transfer coefficient is set at 10 W/m². K to model the heat dissipation from the surface. The steady-state analysis is conducted to observe the equilibrium temperature distribution across the system once all transient effects have settled. This methodology helps understand both the dynamic and equilibrium thermal behaviors of ZrO_2 material under varying thermal conditions.

Results and Discussion

The steady-state analysis of the ZrO_2 rack plate revealed a relatively uniform temperature distribution, as expected (Fig. 2). The highest temperatures were concentrated on the top surface, where the applied heat flux was maximum. However, due to heat conduction throughout the plate, the temperature gradient became more evenly spread over time. The temperature range in the steady-state condition varied from approximately 292.8 K to 452.3 K, indicating effective heat absorption and distribution within the ZrO_2 material. At steady-state, the top surface reached a peak temperature of 452.3 K, while the bottom surface stabilized at ~292.8 K, confirming a temperature gradient of 159.5 K. This demonstrates effective heat absorption and conduction

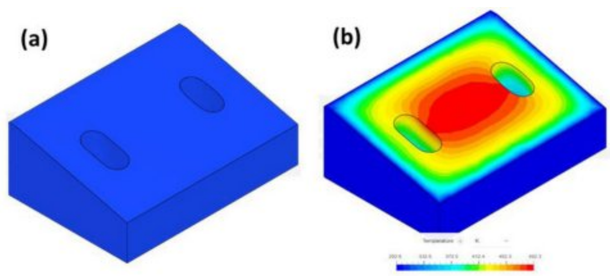

Fig. 2. Thermal behavior of a ZrO_2 rack plate (Steady state condition).

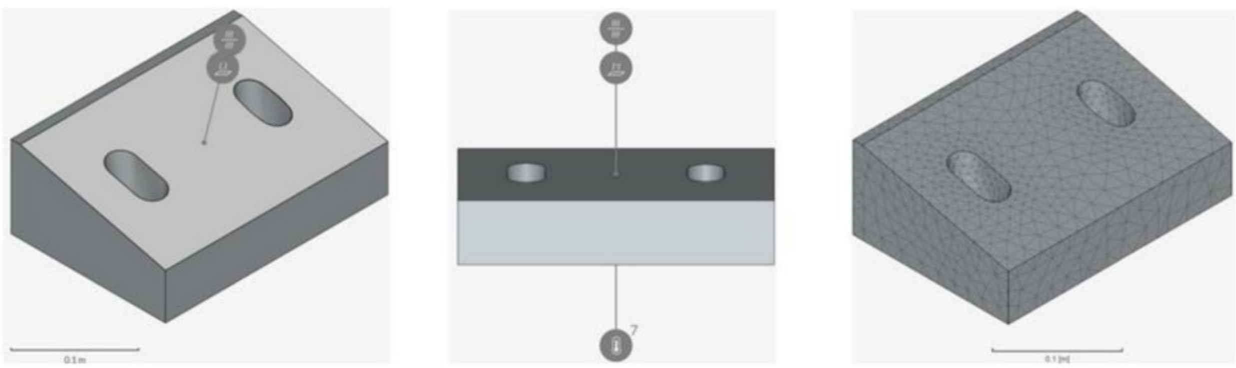

Fig. 1. Rack plate Model used for the current study (ZrO_2).

Table 1.

Metric	Acceptable Range	Min	Max	Average	99.99-th Percentile
Non-Orthogonality	0.0 to 88.0	0.0	60.0	29.5	60.0
Edge Ratio	0.0 to 100.0	1.0	3.0	1.7	3.0
Volume Ratio	0.0 to 100.0	1.0	5.9	1.7	5.9
Aspect Ratio	0.0 to 100.0	6.0	13.8	9.4	13.8
Tetrahedral Aspect Ratio	0.0 to 100.0	6.0	13.8	9.4	13.8
Skewness	0.0 to 100.0	0.1	0.8	0.3	0.8

through the ZrO_2 plate. The uniform temperature distribution indicates efficient thermal transport, ensuring stability in high-temperature applications.

The transient thermal analysis provides insights into the time-dependent heat transfer behavior of the ZrO_2 rack plate (Fig. 3). As heat flux is applied, the temperature at various locations gradually increases over time. At t = 10s, the temperature across different points ranges between 297.8 K and 303.35 K, indicating the initial response of the material to the applied heat. By t = 50s, temperatures reach values between 307.3 K and 311.5 K, demonstrating progressive heat conduction across the plate.

As the simulation progresses, the temperature rise slows down, suggesting that the system is approaching thermal equilibrium. At t = 100s, the maximum temperature recorded is 318.1 K, while the minimum temperature is 316.1 K, indicating that the transient response is converging towards the steady-state solution. Analyzing the rate of temperature increase helps estimate the time required to reach steady-state conditions. The average temperature increase in the first 10 seconds is approximately 5 K, whereas in the next 40 seconds (from 10s to 50s), the rise is around 9 K. However, in the last 50 seconds (from 50s to 100s), the increase slows down to only 6.6 K, highlighting the diminishing thermal gradient as heat redistributes uniformly. By t = 90s, the maximum temperature (317.02 K) is within 1% of the final steady-state temperature (318.1 K). This suggests that the system requires approximately 80-100s to reach near-equilibrium conditions under the given boundary conditions.

The temperature values at different points indicate non-uniform heating, with variations observed across the plate. The highest temperatures are consistently recorded in regions receiving direct heat flux, while lower values appear in areas with enhanced heat dissipation. The data suggests that thermal gradients persist until t = 90-100s, beyond which uniform heat distribution is nearly achieved. Additionally, locations with higher temperatures exhibit a more gradual temperature increase over time (Fig. 4), consistent with the heat conduction properties of ZrO_2. This aligns with expectations for ceramic materials, which have high thermal resistance and slow heat diffusion rates.

The transient analysis highlights the importance of thermal response time in practical applications. In real-world conditions, understanding how long the ZrO_2 plate

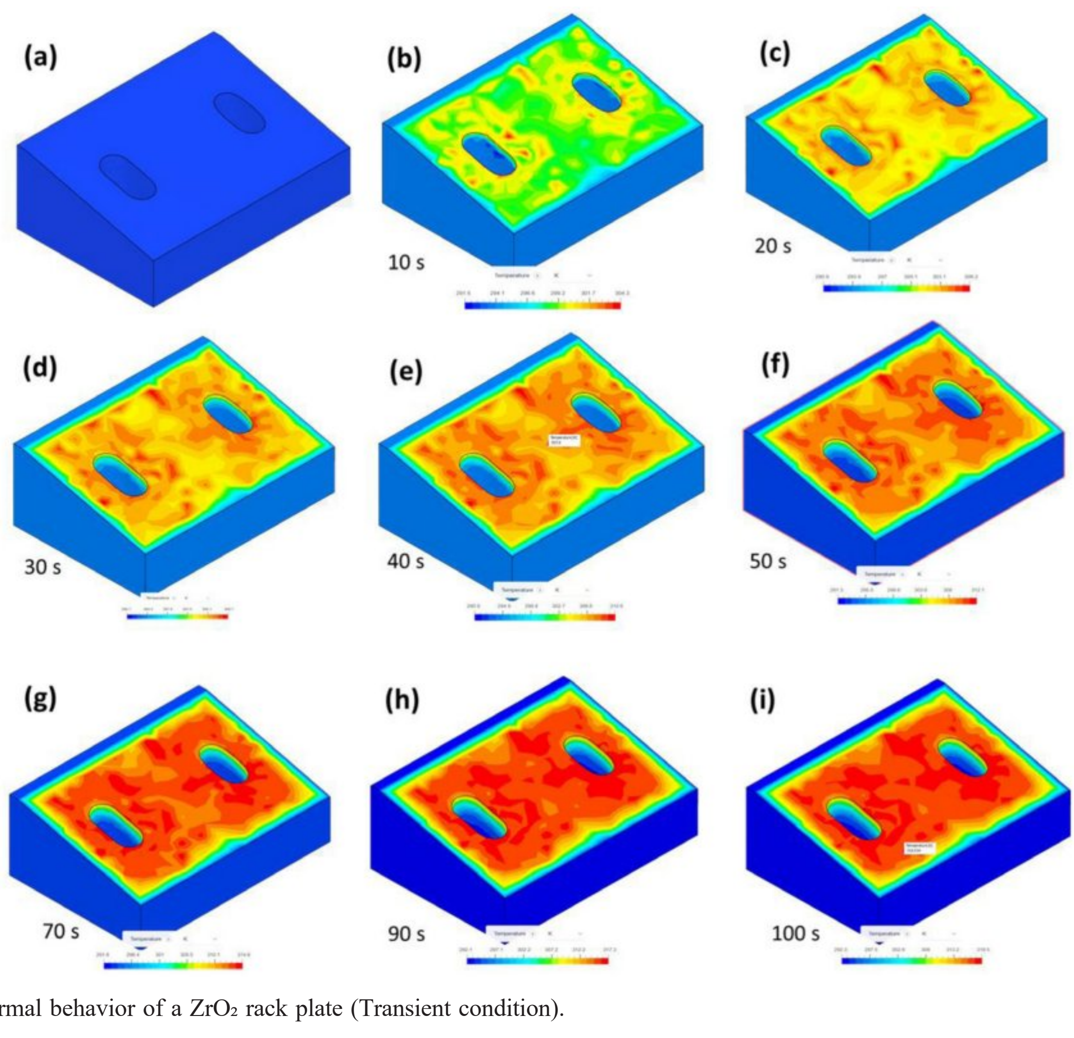

Fig. 3. Thermal behavior of a ZrO_2 rack plate (Transient condition).

takes to reach thermal stability is crucial for ensuring operational efficiency. Components exposed to repeated heating cycles may experience thermal fatigue if rapid temperature fluctuations occur. The results indicate that a preheating time of 90-100s may be required to ensure uniform temperature distribution before the plate reaches steady-state operation. Furthermore, the gradual heat buildup emphasizes the need for effective heat dissipation strategies. Optimizing convection conditions or modifying surface features (such as perforations) could enhance heat removal and reduce localized thermal stresses.

When compared to the steady-state thermal analysis, the transient results show that the system undergoes a progressive transition, with initial temperature differences of over 20 K across different points at t = 10s, which reduces to ~10 K by t = 50s. By t = 100s, the temperature variation across the plate is minimal (~2 K), indicating a near-uniform distribution. The steady-state peak temperature (452.3 K) is significantly higher than the transient values observed in this dataset, suggesting that full thermal equilibrium under higher heat flux conditions would take longer. The steady-state results provide an understanding of the heat dissipation behavior of the ZrO_2 plate. A balance between the applied heat flux and the convective cooling was observed, leading to a well-defined thermal gradient. Analyzing the temperature profile helped in identifying whether heat accumulation occurs in specific regions or if a more uniform distribution is achieved. The results confirm that while the material effectively dissipates heat, certain regions remain hotter due to the applied surface heat flux.

The presence of holes in the ZrO_2 rack plate significantly influenced the temperature distribution. Both transient and steady-state results showed that these perforations created localized cooler regions. This effect could be attributed to changes in heat flow paths or enhanced convective cooling in these areas. Understanding the thermal gradients around the holes is essential for optimizing the design of the plate, ensuring efficient heat dissipation without introducing excessive thermal stress concentrations.

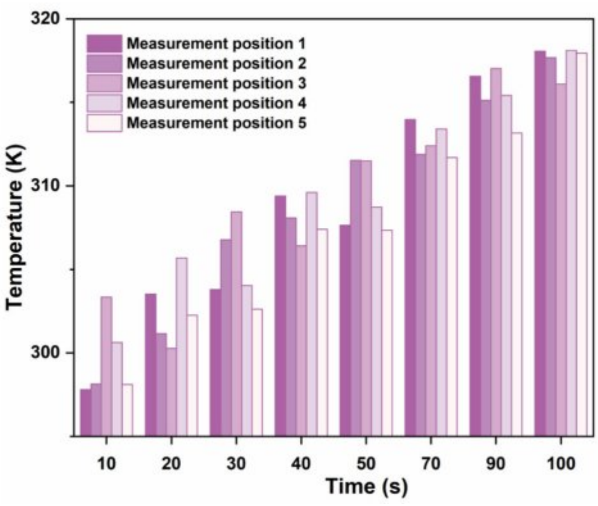

Fig. 4. Transient temperature evolution of the ZrO_2 rack plate over time. The graph illustrates the progressive temperature increase at different locations, showing the system's approach to thermal equilibrium. At t = 10s, the temperature ranges from 297.8 K to 303.35 K, gradually rising to 318.1 K at t = 100s.

Practical Implications and Application Relevance

The thermal behavior of the ZrO_2 rack plate has direct implications for its practical applications. Understanding steady-state and transient temperature characteristics is essential for predicting thermal stress development, which can impact the mechanical integrity and longevity of the component. In high-temperature applications, thermal gradients may induce stresses that could lead to material fatigue or failure. Therefore, integrating the insights from this study into the design process can help optimize the plate for enhanced durability and performance.

Conclusion

The transient thermal analysis of the zirconia rack plate demonstrated a gradual temperature increase over time, with the system nearing thermal equilibrium within 100s under the given boundary conditions. The maximum temperature rose from 303.35 K at t = 10s to 318.1 K at t = 100s, indicating a consistent but decelerating heat absorption rate. The results showed that by t = 90s, the temperature reached 317.02 K, within 1% of the final steady-state temperature, suggesting that complete thermal stabilization would require slightly more time. The effect of perforations on heat distribution was evident, with local temperature reductions of ~20 K due to enhanced convective cooling. The comparison with steady-state results (peak temperature of 452.3 K) highlighted that full equilibrium had not been reached within 100s, emphasizing the need for extended simulation durations for complete thermal stabilization analysis. These findings are critical for understanding the thermal response of zirconia ceramics in high-temperature applications, where controlling heat distribution and predicting equilibrium time are essential for optimizing performance and preventing thermal stress. Future work should focus on experimental validation and extended transient analysis to refine these numerical predictions.

Acknowledgement

This work was supported by the Key scientific research project of Henan Province (25A560023).

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