Analysis of Temperature Distribution of Graphite in HTGR Due to Radiation-Induced Variation of Thermal Conductivity

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ABSTRACT

High-Temperature Gas-cooled Reactors (HTGR) employ graphite blocks as core structural and moderator materials. Under neutron irradiation, graphite undergoes microstructural changes that significantly degrade its thermal conductivity. In this study, we modeled the variation of graphite thermal conductivity as a function of neutron fluence and temperature, and performed CFD simulations to analyze the resulting temperature distribution inside the reactor core. The results demonstrate a considerable rise in peak temperature near the outlet due to reduced thermal conductivity, highlighting the importance of accurate material property modeling in reactor safety analysis.

INTRODUCTION

High-Temperature Gas-cooled Reactor (HTGR)

HTGR is a next-generation nuclear reactor that uses graphite blocks as both moderator and structural material. Its helium coolant and high outlet temperature offer enhanced thermal efficiency.

Radiation-Induced Thermal Conductivity Degradation

Under neutron irradiation, graphite experiences microstructural damage, leading to a significant reduction in thermal conductivity. This affects core temperature distribution and reactor thermal-fluid performance.

Need for Accurate Modeling

Changes in temperature can cause thermal stress in structural components. For safe, long-term operation, it is crucial to quantify the thermal conductivity degradation and analyze its effect on core thermal behavior using CFD.

METHODOLOGY

Graphite Selection

Three nuclear-grade graphite types were selected for analysis: IG-110, H-451, and G-347. These materials are widely used in HTGRs and exhibit distinct thermal conductivity degradation behaviors under neutron irradiation.

Thermal Conductivity Modeling

Experimental data for irradiated graphite were fitted using third-order polynomial functions. The thermal conductivity $k(T,\phi)$ was modeled as a function of temperature and neutron fluence.

- Neutron fluence levels: 0, 0.2, 1, 3, 6 × 10^{25} n/m²
- Each material had a unique degradation curve applied in simulation.

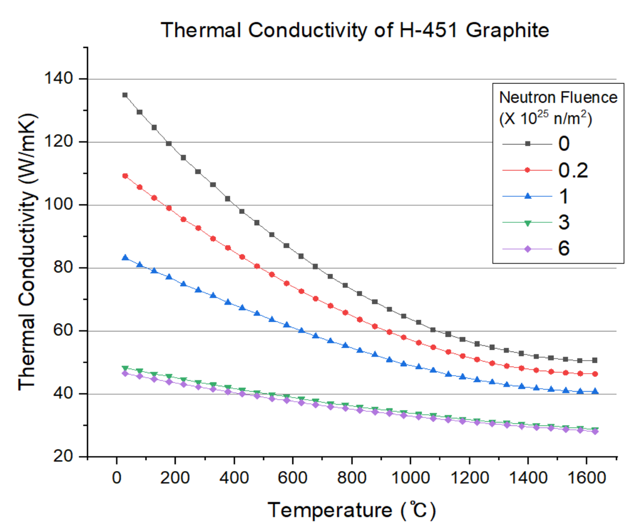

Fig. 1. Temperature dependence of thermal conductivity for H-451 graphite.[3]

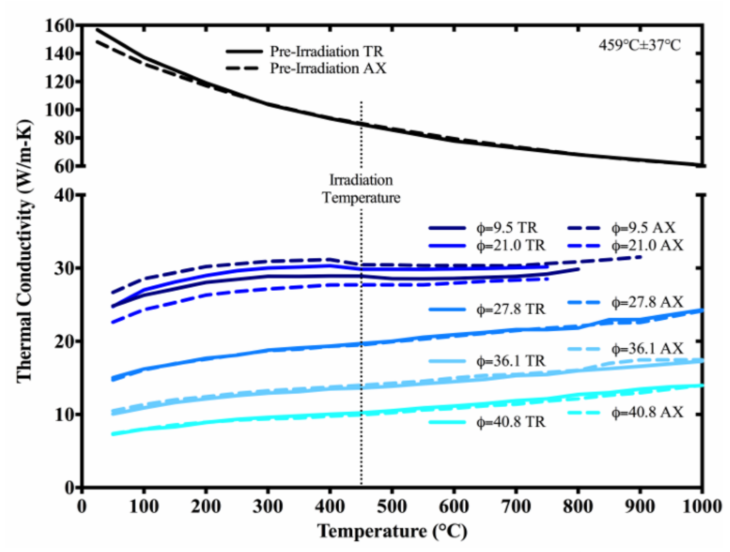

Fig. 2. Temperature dependence of thermal conductivity for IG-110 graphite.[2]

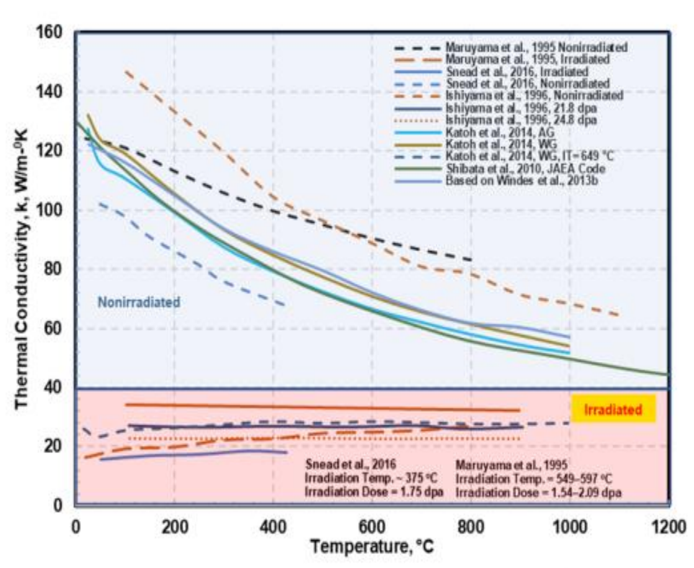

Fig. 3. Temperature dependence of thermal conductivity for IG-110 graphite.[6]

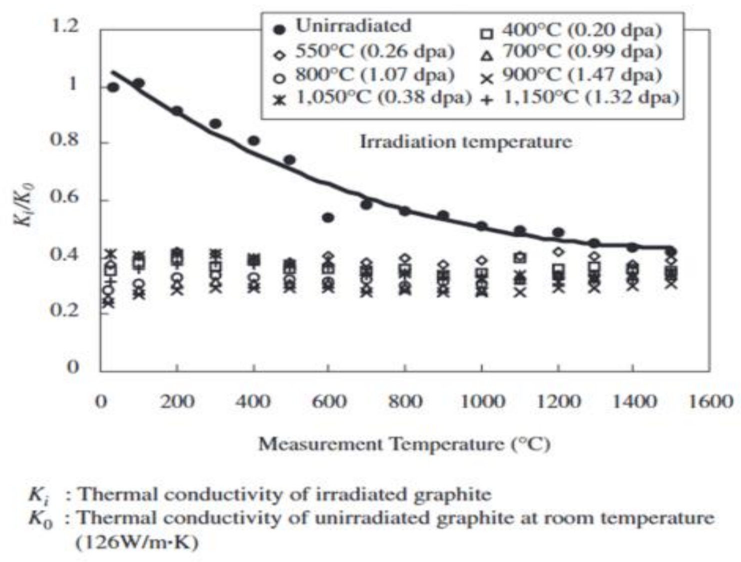

Fig. 4. Temperature dependence of thermal conductivity for G-347 graphite.[5]

CFD Simulation Setup

- Geometry: Single graphite block based on MHTGR-350 design
- Tool: ANSYS Fluent v24.1
- Mesh: ~16.8 million cells
- Conditions: Mass flow rate and heat generation set according to MHTGR-350 documentation
- Goal: Evaluate maximum and average temperature under different irradiation levels

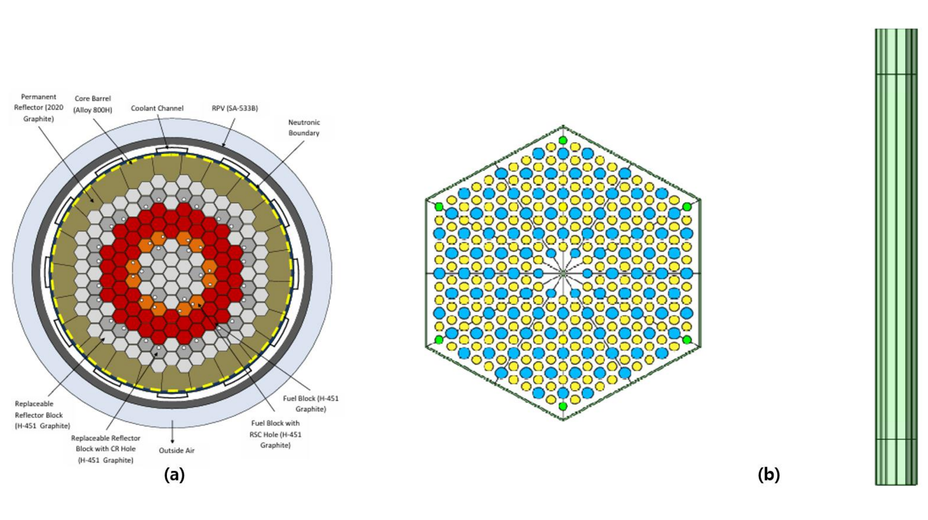

Fig. 5. (a) Schematic of MHTGR design.[3]
(b) Geometry of graphite block model

RESULTS AND DISCUSSION

Temperature Increase Due to Neutron Irradiation

As neutron fluence increased, both maximum and average temperatures of graphite blocks rose across all material types.

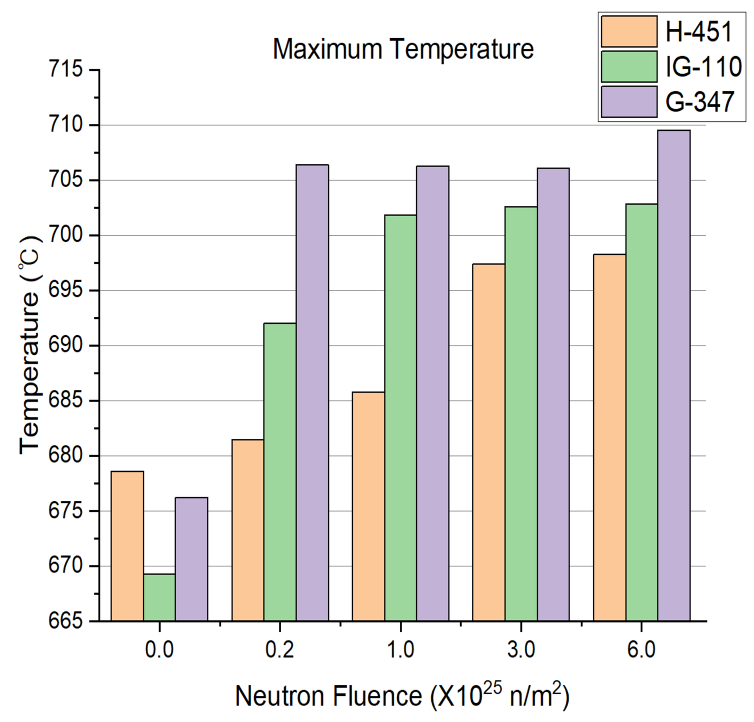

Fig. 6. Graphite average temperature.

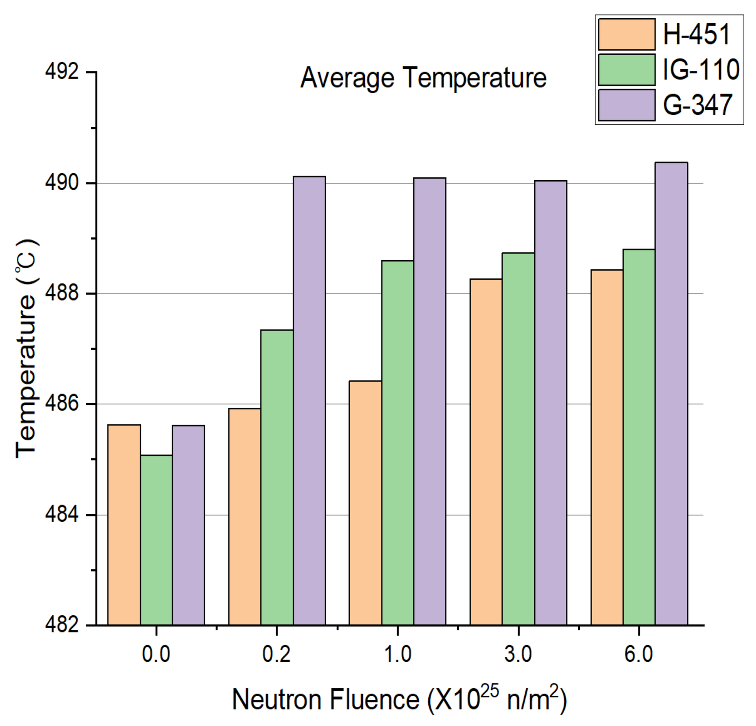

Fig. 7. Graphite average temperature.

Temperature Distribution

Temperature of the graphite block increases toward the outlet. In the IG-110 block at high fluence (6×10^{25} n/m²), the highest temperature region appeared near the outlet, slightly offset from the geometric center. This may cause localized thermal stresses, relevant for structural integrity evaluation.

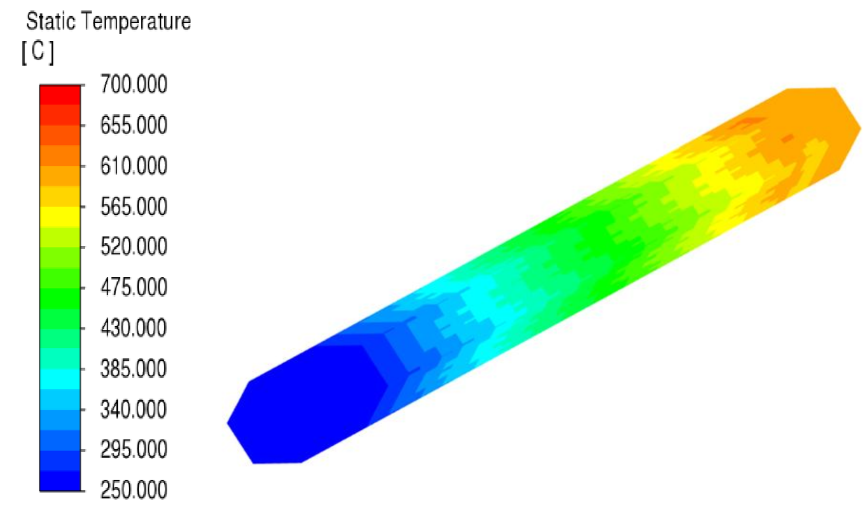

Fig. 8. Temperature distribution of the graphite block

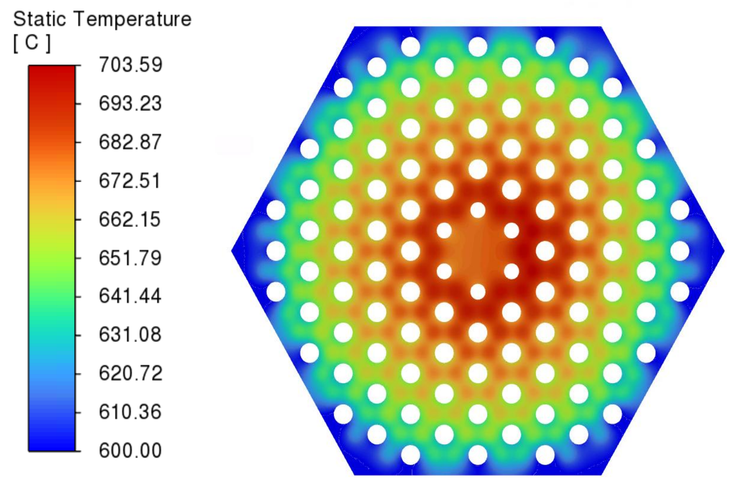

Fig. 9. The cross-section of IG-110 graphite at the point where the maximum temperature occurs. (5 cm away from outlet)

Safety Margin Maintained

Despite the temperature increase, the maximum temperature remained < 710°C, far below the graphite melting point (~3650°C). Suggests no critical thermal safety issues under expected irradiation conditions in HTGRs.

CONCLUSION

1. Neutron irradiation causes a decrease in graphite thermal conductivity, leading to an increase in both maximum and average temperatures within the HTGR core.
2. Among the tested materials, IG-110 and G-347 showed a temperature increase of over 30°C at the highest fluence level.
3. Despite these changes, the maximum temperature remained below 710°C, ensuring a large safety margin against graphite melting.
4. The results confirm that radiation-induced thermal conductivity degradation must be considered in HTGR thermal analysis, but does not compromise structural safety under expected operating conditions.

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