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Assessing the Impact of Effective Thermal Conductivity on Gas-Cooled Reactor Transients in RELAP5-3D

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INTRODUCTION

High-temperature gas-cooled reactors (HTGRs) are a relatively mature advanced reactor concept of interest to industry and government for near-term deployment. These systems feature passive safety through low power density, coated particle fuels, and large graphite volumes that lead to a slow heat up. In loss-of-flow transients, cooldown is achieved through conduction and radiation heat transfer [1]. In prismatic-block-type reactors, such as the modular high-temperature gas-cooled reactor, mHTGR-350, coolant holes and fuel compacts alter the heat flow through the blocks. To capture this effect in systems codes like the Reactor Excursion and Leak Analysis Program 3D (RELAP5-3D), effective thermal conductivity (ETC) relationships must be used to appropriately degrade the thermal conductivity. This work presents an assessment of the ETC impact on block-type gas-cooled reactor performance in pressurized conduction cooldown (PCC) and depressurized conduction cooldown (DCC) transients. We ran PCC and DCC models with bulk material thermal conductivity and ETC for both the mHTGR-350 and High-Temperature Test Facility (HTTF) to determine the ETC impact on transient performance.

Effective Thermal Conductivity

We have identified several relationships to represent the ETC of systems containing more than one material for multiple geometries. For Fort St. Vrain–style blocks, two relationships were identified that may be applicable for representing ETCs, both of which are for a block containing an array of cylinders. Both relationships rely on the thermal conductivity of the bulk material (k_{block}), the thermal conductivity of the coolant channels (k_{He}), and the coolant channel volume fraction in the block (ϕ).

The first relationship we identified was developed by Lord Rayleigh and has two components to the ETC: a component parallel to the coolant channels and a component perpendicular to the coolant channels. This approach is described in greater detail in Ref. [2]. We refer to the parallel and perpendicular components collectively as the "Rayleigh relationship." The parallel component of the thermal conductivity is given by Eq. 1, and the perpendicular component is given by Eq. 2.

$$k_{eff,parallel} = k_{block} + \frac{k_{block}(k_{He} - k_{block})}{k_{block}}\phi \qquad (1)$$

$$k_{eff,\perp} = k_{block} + k_{block}\frac{2\phi}{\frac{k_{He}+k_{block}}{k_{He}-k_{block}} - \phi + \frac{k_{He}-k_{block}}{k_{He}+k_{block}}(0.30584\,\phi^4 + 0.013363\phi^8)} \qquad (2)$$

The Rayleigh relationship was developed for cylindrical holes in a square lattice, thus it may not represent an exact ETC for the Fort St. Vrain–style prismatic block, but it provides a starting point for assessing the ETC impact on PCC and DCC transients.

The second identified relationship for the ETC of a similar geometry to the Fort St. Vrain blocks was developed for implementation in the HTGR Gas Multicomponent Mixture Analysis (GAMMA+) code [3]. The models for heat removal through radiation and conduction in GAMMA+ have been tested against commercial computational fluid dynamics codes and generally found good agreement. The overall model in GAMMA+ includes heat transfer by radiation between blocks, but this work is focused on the ETC model in the blocks. We refer to this relationship, as given in Eq. 3, as the "GAMMA+ relationship."

$$k_{eff} = \frac{1 - \phi\left(\frac{k_{block} - k_{He}}{k_{block} + k_{He}}\right)}{1 + \phi\left(\frac{k_{block} - k_{He}}{k_{block} + k_{He}}\right)} \times k_{block} \qquad (3)$$

Unlike the Rayleigh model, the GAMMA+ model has been tested specifically for a gas-cooled reactor block geometry, providing confidence in its applicability [3].

The mHTGR-350

The mHTGR-350 is a preconceptual design for a prismatic-block-type gas-cooled reactor that was developed as part of a coupled neutronics-thermal-hydraulics benchmark for block-type HTGRs [4]. The mHTGR-350 has a thermal power of 350 MW and uses an annular core design with an inner reflector, a set of fueled rings, and an outer reflector. The fuel is tristructural isotropic particles embedded in graphite fuel compacts at a 35% packing fraction. The prismatic blocks themselves are made of H-451 graphite. The RELAP5-3D model for mHTGR-350 defines a material for the unirradiated H-451 graphite used in the reflectors and a material for irradiated H-451 graphite used in the fueled blocks. The core is modeled as a series of 10 concentric rings, with Rings 4, 5, and 6 representing the fueled rings in the core.

The High Temperature Test Facility

The HTTF is an integral-effects thermal-hydraulics test facility at Oregon State University that represents a ¼-length-scale version of mHTGR-350. The HTTF is electrically heated and can reach up to 2.2 MW. To provide temperatures representative of mHTGR-350 despite the lower power, the prismatic blocks in the HTTF are made of an aluminum-oxide ceramic with a thermal conductivity on the order of a few watts per meter kelvin [5]. Unlike the mHTGR-350, which operates at 6.39 MPa, the HTTF operates at 0.7 MPa. This work descends from an HTTF RELAP5-3D model developed at Idaho National Laboratory [6]. The HTTF RELAP5-3D model defines all the aluminum-oxide blocks as a single material. Examining both the mHTGR-350 and HTTF provides an opportunity for us to assess the impact of ETC at a high thermal conductivity (mHTGR-350) and low thermal conductivity (HTTF). The HTTF RELAP5-3D model also treats the core as a series of 10 concentric rings, with Rings 4, 5, and 6 representing the electrically heated region of the core.

METHODOLOGY

To determine the ETC of mHTGR-350 and HTTF blocks, we plugged the bulk thermal conductivities of the block materials, helium thermal conductivities, and helium volume fractions into the perpendicular Rayleigh equation and GAMMA+ equation for ETC. The graphite thermal conductivity was the irradiated H-451 from the mHTGR-350 RELAP5-3D model [4], the aluminum-oxide thermal conductivity for HTTF was from the HTTF facility description [5], and the helium thermal conductivity was from the RELAP5-3D equation of state.

For the mHTGR-350, the helium volume fraction was based on the area of the Fort St. Vrain block and the total area of coolant channels in the block. The only blocks we considered in determining the ETC for the mHTGR-350 were the fueled blocks. Fig. 1 shows that the Rayleigh perpendicular and GAMMA+ relationships yield comparable ETCs. The degradation in thermal conductivity due to the presence of coolant holes was approximately 31%.

For HTTF, the helium volume fraction was based on the total helium volume fraction in the inner reflector, heated region, and outer reflector. Fig. 2 shows that, once again, the two ETC relationships provide excellent agreement with one another. The reduction in thermal conductivity over the whole core in the HTTF due to the presence of coolant holes ranged from 20% at 478 K to 25% at 1368 K.

The HTTF RELAP5-3D model developed in Ref [6] models the entire facility. The model used in this work is simplified to model just the reactor vessel and reactor cavity cooling system. The coolant flow rate was set at a fixed 1 kg/s, and the inlet temperature was set to 500 K.

The mHTGR-350 PCC is initiated by reducing the coolant flow rate from 157 kg/s to 0 kg/s linearly over 30 seconds. SCRAM occurs at 57 seconds. The mHTGR-350 DCC has the coolant flow go to zero over 20 seconds, and depressurization occurs over the same time period. SCRAM occurs at 27 seconds. The GAMMA+ ETC was used in the RELAP5-3D model for the mHTGR-350 to account for thermal conductivity degradation.

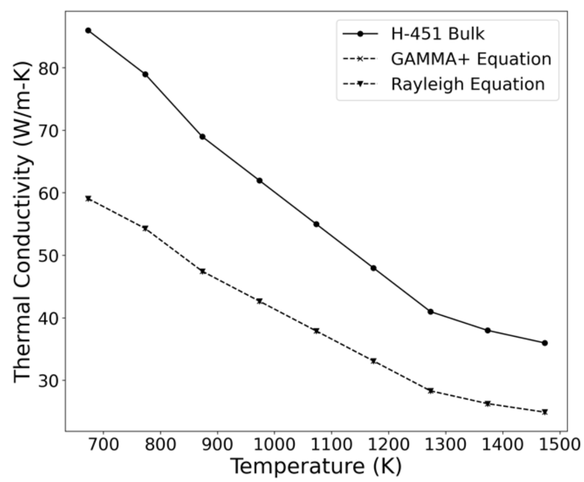

Fig. 1. The mHTGR-350 ETC of H-451 graphite as a function of temperature. ETC results overlap one another on the graph.

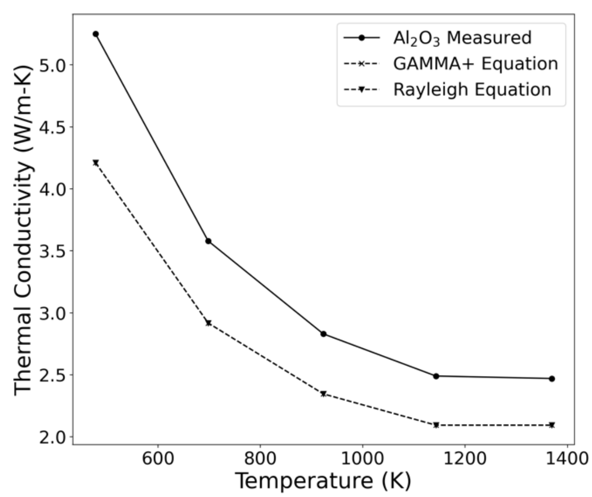

Fig. 2. The HTTF ETC of Al_2O_3 as a function of temperature. ETC results overlap one another on the graph.

In the HTTF models, SCRAM occurs at 0.0 seconds, and the coolant flow rate reduces from 1.0 to 0.0 kg/s over 1 second. For the DCC, the depressurization occurred over 20 seconds. For these calculations, we used the ANS decay heat standard in the HTTF. We used the GAMMA+ ETC in the RELAP5-3D model for the HTTF to account for the degradation in thermal conductivity.

RESULTS

In the mHTGR-350, the impact of ETC was quite small. During a steady state, the difference in fuel temperatures (Fig. 3) was small. The difference in peak fuel temperature between the bulk H-451 thermal conductivity and ETC is 5 K, and the largest difference in fuel temperature was approximately 10 K.

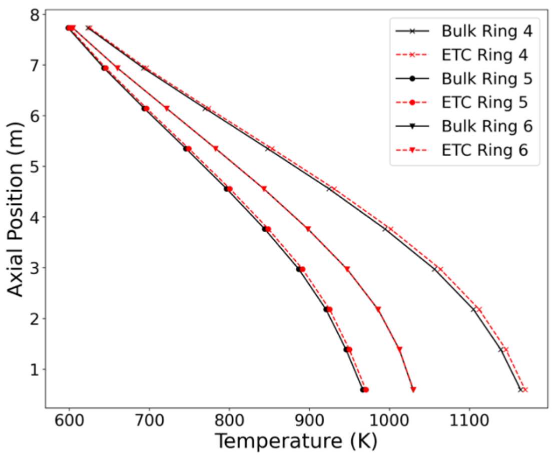

Fig. 3. Steady-state temperature distributions in the mHTGR-350 with and without accounting for ETC.

During the PCC, the difference in peak fuel temperatures was also small. The largest difference in peak fuel temperature over 48 hours was just 6 K. The fuel temperatures in PCC can be seen in Fig. 4. In the DCC, the peak fuel temperature differs by only 7 K with and without the ETC. Peak fuel temperatures for the DCC can be seen in Fig. 5. In both cases, we see that the difference in peak fuel temperature is small. For the first 10 hours of the transient, the temperatures follow one another very closely. After 10 hours, the model using bulk graphite thermal conductivity cools down faster due to the greater heat removal by conduction, but the general behavior is the same in both models. The impact of ETC in the mHTGR-350 RELAP5-3D model does not significantly change the performance of the reactor during PCC or DCC. The minimum in peak fuel temperature that occurs around 3 hours arises due to the shift in location of peak fuel temperature. In steady state, the peak fuel temperature is at the bottom of the core, but as the transients develop, the location of peak fuel temperature shifts upward. The bottom of the core cools off, leading to the behavior prior to 3 hours, but the top of the core heats up, leading to the behavior seen after 3 hours.

In the HTTF, we consider block temperatures rather than fuel temperatures because the system is heated with electrical heaters rather than nuclear fuel. The aluminum-oxide ceramic blocks in the HTTF provide a good parallel to the graphite blocks in the mHTGR-350. The steady-state difference in peak block temperature is 17 K, about 1.4% the temperature.

In the PCC for the HTTF, peak block temperature rises for the first 2 minutes before cooling down. The peak block temperature using the bulk Al_2O_3 thermal conductivity is 1,233 K, and the peak block temperature using the ETC is 1,252 K, a difference of just 19 K. Fig. 6 shows that the difference in peak block temperatures gets larger over time. The growing differences in block temperatures over time stem from faster heat removal through conduction in the bulk thermal conductivity model. The differences in the PCC block temperatures would not meaningfully impact the HTGR safety case.

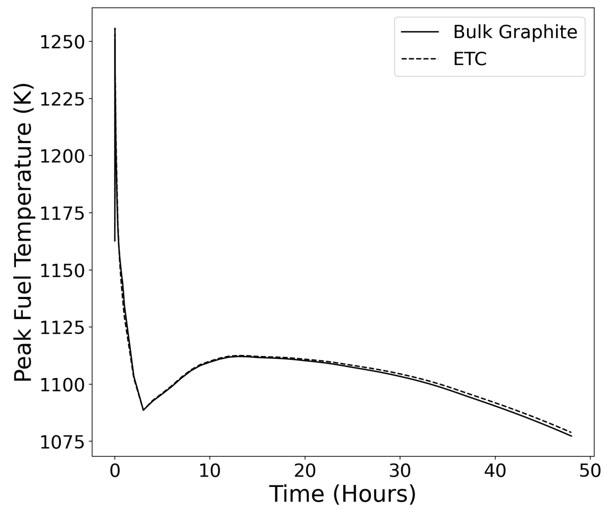

Fig. 4. Peak fuel temperatures in the mHTGR-350 PCC.

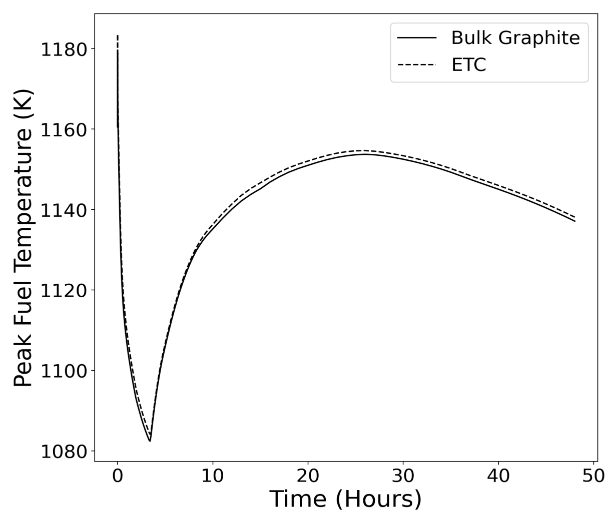

Fig. 5. Peak fuel temperatures in the mHTGR-350 DCC.

The HTTF DCC generally undergoes the same behavior as the PCC. The maximum block temperature occurs within the first few minutes of the transient, and the difference in maximum temperature is 20 K. Notably, the difference between the bulk aluminum-oxide thermal conductivity and ETC block temperatures during the cooldown period is larger for the DCC than the PCC. In the DCC, the difference in block temperatures exceeds 40 K at

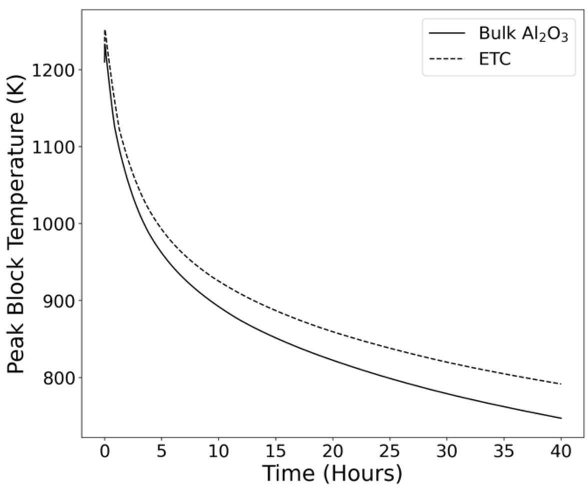

Fig. 6. Peak block temperatures in the HTTF during the PCC.

17.67 hours, whereas it takes 27.15 hours to reach the same difference in the PCC. This difference likely stems from the presence of natural circulation in the PCC, reducing the relative contribution of conduction to the cooldown as opposed to the DCC, which lacks natural circulation. The location of peak block temperature shifts upward in HTTF over time, but this shift is much slower than in the mHTGR-350; thus, we do not see a local minimum in peak block temperature in HTTF. Once again, the differences in block temperatures are not significant enough to have a meaningful impact on the HTGR safety case.

CONCLUSIONS

The presence of coolant channels in prismatic block-type gas-cooled reactors reduces heat transfer through the blocks. Accurate modeling of conduction cooldown transients in these systems in RELAP5-3D requires use of an ETC that accounts for the presence of coolant channels. By implementing an ETC in RELAP5-3D models for the mHTGR-350 and the HTTF, we have demonstrated that while ETCs do lead to higher temperatures than using the bulk thermal conductivity of the block material, the reduction in thermal conductivity does not have significant implications on the safety case of these systems. Peak fuel temperatures in the mHTGR-350 differ by less than 10 K for 48 hours in PCC and DCC. In the HTTF, the maximum block temperature during PCC and DCC differs by approximately 20 K. The biggest impact of the ETC is to slow down conduction heat removal, leading to the temperature differences between models using bulk thermal conductivity and models using ETC to grow as the reactor cools down.

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NOMENCLATURE

k_{eff}= ETC
k_{block}= Bulk thermal conductivity of the block material
k_{He}= Helium thermal conductivity
ϕ = Helium volume fraction in the block

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