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Changing the World's Energy Future

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Flattening the Radial Temperature Profile across the Transformational Challenge Reactor Core

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INTRODUCTION

The Transformational Challenge Reactor (TCR) program [1] is demonstrating an agile development approach to advanced nuclear reactor design, which has traditionally utilized a linear design process. In leveraging artificial intelligence, additive manufacturing, advanced materials, and cutting-edge modeling and simulation, the TCR program aims to minimize the high cost and lengthy deployment timelines now standard in the nuclear industry [2, 3]. Within a relatively short period of time, a robust and mature advanced gas-cooled reactor was iteratively designed under the TCR program, using these cutting-edge technologies.

The TCR (see Fig. 1) is a 3 MWt gas-cooled microreactor fueled with uranium nitride (UN) tristructural isotropic (TRISO) fuel particles. Though manufactured via traditional means, these UN TRISO particles are loaded into additively manufactured silicon carbide (SiC) cans [4]. Once loaded with TRISO particles, the SiC cans are densified using a chemical vapor infiltration process. The additively manufactured SiC enables significantly more freedom in the design of the fuel form than could ever be achieved using traditionally manufactured SiC [5]. The helium coolant, pressurized to 5 MPa, enters the core at 300°C and nominally exits it at 500°C.

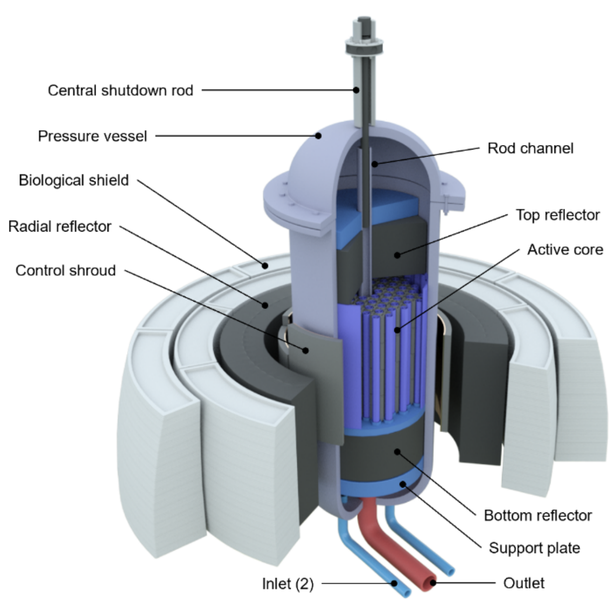

Fig. 1. Artist rendering of the TCR core, vessel, and reflector layout (not to scale).

Typically, the most thermally limiting components in any reactor design are the fuel assemblies in the core center. To provide a wide thermal margin in these central fuel assemblies, the flow may be biased toward the center of the core to more effectively cool these fuel assemblies with more power deposition and flatten the core's radial temperature distribution. An analytical fluid model of the TCR core was developed to explore methods for biasing the flow away from the cooler outer fuel assemblies and towards the hotter inner ones. Higher-fidelity models developed in STAR-CCM+ 2020.3.1, a computational fluid dynamics code, were then utilized to verify the analytical model's findings.

Modeling Methods

The analytical model utilized a simplified version of the core layout, as shown in Fig. 2. The core contains 54 fuel assemblies arranged into four radial rings, as shown in Fig. 3. The eight relatively complicated coolant channels that surround and run through the fuel assemblies were simplified into three cylindrical channels using their hydraulic diameters. The radial power-peaking factors are also shown in Fig. 3, with the inner ring having the highest value at 1.326. The inlet temperature and mass flow rate were set to 300°C and 2.89 kg/s, respectively, to achieve an average outlet temperature of 500°C. The thermophysical properties of the helium coolant were defined as a function of temperature at the system pressure of 5 MPa and were obtained from the National Institutes of Standards and Technology's WebBook [6].

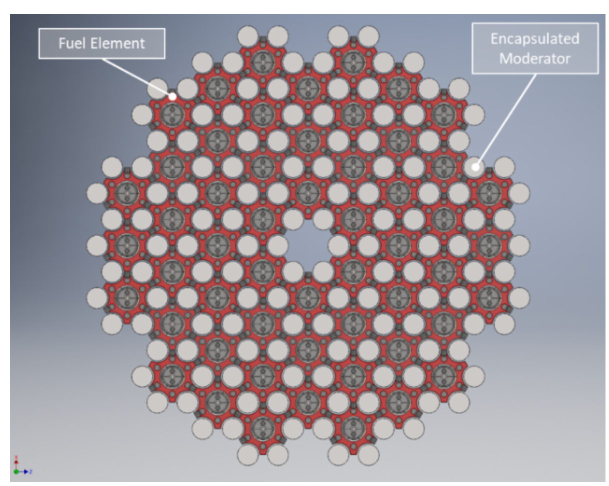

Fig. 2. Top-down view of the TCR core layout.

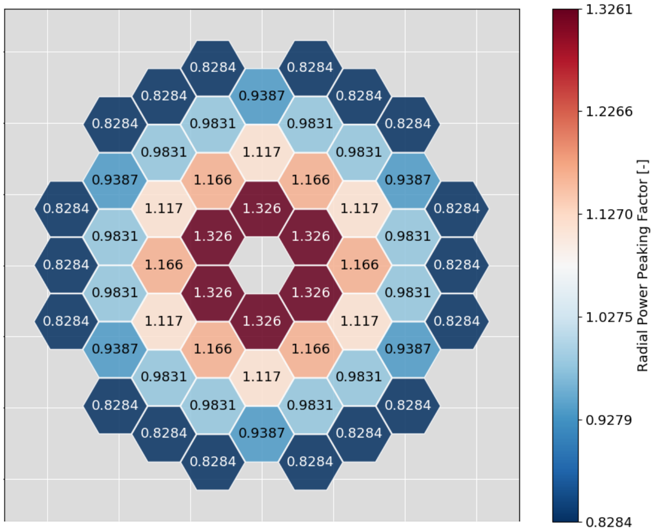

Fig. 3. Radial power-peaking factors in each fuel assembly.

There are four unknown quantities in each fuel assembly: the mass flow rate through each of the three coolant channels, and the average temperature at the outlet of the fuel assembly. Thus, four equations are required to obtain a solution for a given fuel assembly. The following set of equations provide the mathematical framework for developing a simplified thermal-fluidic solution for a fuel assembly—a framework easily expandable to the entire core.

The minor loss due to sudden contraction of a channel, k_{con}, was estimated using:

$$k_{con} = 0.5\left(1 - \frac{d^2}{D^2}\right) \tag{1}$$

where D and d are the flow diameters before and after the contraction, respectively [7]. Due to the non-circular nature of the fuel assembly's channels, the hydraulic diameter was calculated for each channel using:

$$d_h = \frac{4A}{P} \tag{2}$$

where A and P are the flow area and wetted perimeter of a coolant channel, respectively. The loss due to sudden expansion, k_{exp}, of a channel was calculated using:

$$k_{exp} = \left(1 - \frac{D^2}{d^2}\right)^2 \tag{3}$$

where d and D are the flow diameters after and before the expansion, respectively [8]. Major losses due to friction, k_f, through the channels were calculated using:

$$k_f = \frac{fL}{D} \tag{4}$$

where f is the Darcy friction factor, L is the channel length, and D is the channel diameter. To estimate the Darcy friction factor for the turbulent flow, the equation developed by Haaland was utilized:

$$\frac{1}{f^{1/2}} = -1.8log\left[\frac{6.9}{Re_d} + \left(\frac{\epsilon/d}{3.7}\right)^{1.11}\right] \tag{5}$$

which varies by less than 2% from the Colebrook equation [8]. Eq. (5) includes the Reynolds number, Re_d, defined by:

$$Re_d = \frac{\rho V D_h}{\mu} \tag{6}$$

where ρ, μ, and V are the fluid density, viscosity, and average channel velocity, respectively. Wall roughness height, ϵ, is also included in Eq. 6; however, all channel walls were assumed to be smooth. Using the k losses calculated via Eqs. (1), (3), and (4), the pressure drop, ΔP, can be estimated by:

$$\Delta P = \frac{1}{2} k_{loss} \rho V^2 \tag{7}$$

where V is the average channel velocity responsible for frictional losses. For expansions and contractions, the velocity is taken from the smaller channel. The total pressure drop through a channel, ΔP_{ch}, was calculated by summing the contraction, expansion, and frictional losses through a fuel assembly, using:

$$\Delta P_{ch} = \sum \Delta P_{ch,con} + \sum \Delta P_{ch,f} + \sum \Delta P_{ch,exp} \tag{8}$$

While the pressure drop through each of the three simplified channels flowing through a fuel assembly should be equal, the flow velocities in each channel will differ due to each channel's varying geometry. This produces a total of three unknowns, necessitating three equations to solve for them. The three equations are:

$$\Delta P_{ch,1} = \Delta P_{ch,2} \tag{9}$$

$$\Delta P_{ch,2} = \Delta P_{ch,3} \tag{10}$$

$$\rho_{inlet} V_{inlet} A_{inlet} = \sum_{i=1}^{3} \rho_{ch,i} V_{ch,i} A_{ch,i} \tag{11}$$

where $\Delta P_{ch,1}$, $\Delta P_{ch,2}$, and $\Delta P_{ch,3}$ are the total pressure drops through channels 1, 2, and 3, respectively. Eq. (11) describes the mass balance through the fuel assembly. Since the fuel generates heat in the model, the coolant temperature will rise as it flows around/through the fuel assemblies. The following classic energy balance equation was utilized to calculate the average outlet temperature of each fuel assembly, T_{outlet}:

$$Q = \dot{m}_{inlet} c_p (T_{outlet} - T_{inlet}) \tag{12}$$

where Q is the total power generated in each fuel assembly, c_p is the heat capacity of the coolant, and T_{inlet} the average inlet temperature. To account for the axial variation in power along each fuel assembly, as well as the change in the fluid properties as the temperature of the helium coolant rises in the channels, the model was divided into eight axial segments along the fueled section of the core.

Using Eqs. (1)–(12) , an analytical model of a fuel assembly was developed. To obtain a solution for the entire TCR core, the four-equation set for each of the 54 fuel assemblies are combined and solved simultaneously.

Due to simplifications assumed in the analytical model, a numerical model of the TCR core was also developed in STAR-CCM+. Essentially, once a design was established for flattening the temperature distribution using the analytical model, a numerical model of that design was built in STAR-CCM+ to verify that the design behaved as expected. To save computational time and resources, only 1/12th of the core was modeled using symmetry planes, as shown in Figure 4.

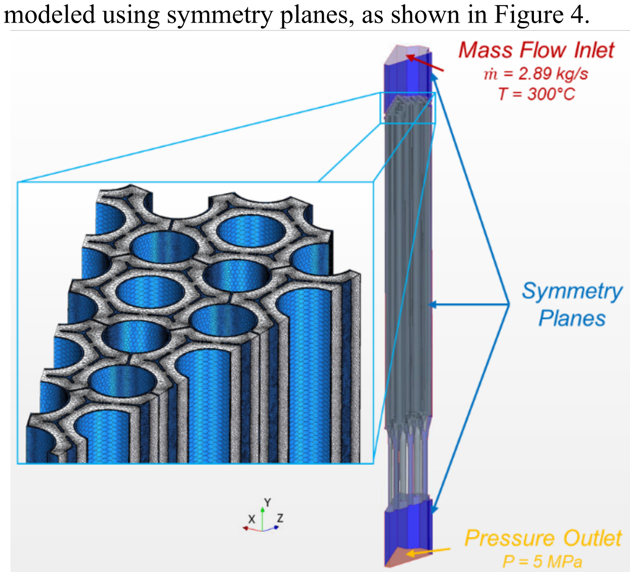

Fig. 4. 1/12th TCR core geometry in STAR-CCM+.

Turbulent flow was modeled using the Reynolds-averaged Navier-Stokes SST k-ω turbulence model. To accurately capture the turbulent boundary layer, a prism layer mesh was added to the mesh of the helium coolant, adding mesh refinement near the walls in the model. Though a mesh independence study has not yet been conducted, when comparing the STAR-CCM+ model with the analytical model, the variation in flow properties (e.g. pressure drop and velocity) were within 3%. All walls were assumed to be no-slip and smooth, and the helium gas coolant was assumed to be compressible and steady. The material properties obtained from the National Institutes of Standards and Technology's WebBook for the analytical model were also utilized in the STAR-CCM+ model.

As seen in Fig. 4, the mass flow rate and temperature were specified at the inlet of the model, and the pressure was set to 5 MPa at the outlet. Heat generation in the fuel varied in each of the four radial rings. As shown in the zoomed view in Figure 14, polyhedral cells were utilized to mesh the helium and the fuel assemblies.

RESULTS

The baseline results from the analytical and STAR-CCM+ models are shown at the top and bottom of Fig. 5, respectively. The value in the center of each fuel assembly is the average helium temperature at that assembly's outlet. As expected, the highest coolant temperatures are in the inner ring. Both models exhibit very similar solutions, with a predicted radial temperature gradient of ~110°C and a pressure loss through the core of ~26 kPa.

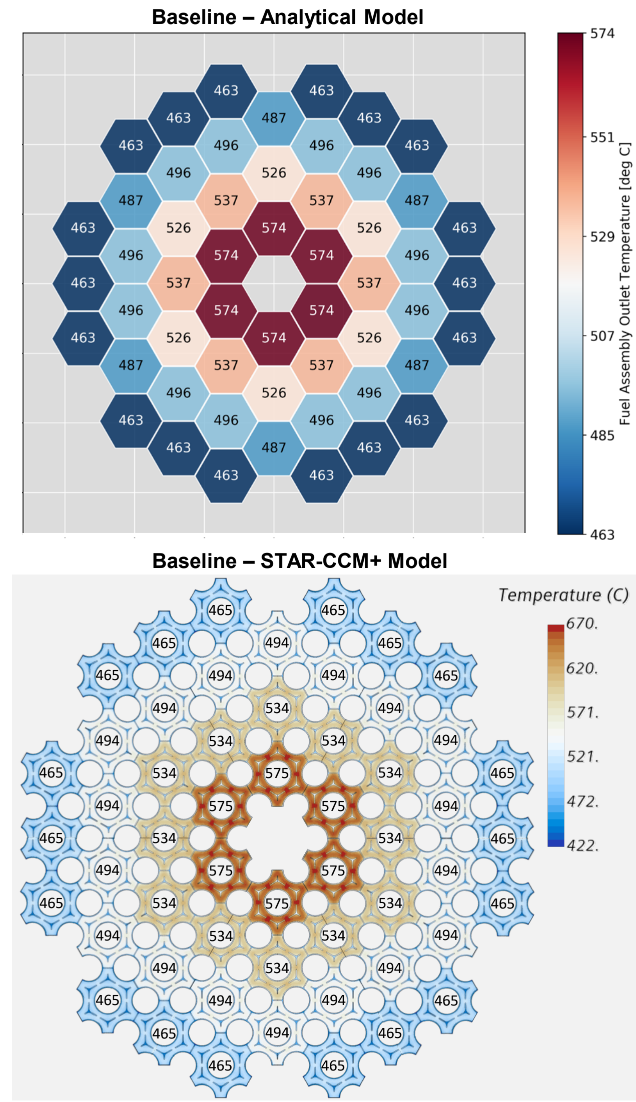

Fig. 5. Baseline case, average helium temperature at the outlet of each fuel assembly for the analytical (top) and STAR-CCM+ (bottom) models.

To flatten the temperature distribution, a few different methods were explored including adding an orifice plate above or below the core's fuel assemblies. Unfortunately, the orifice plate was insufficient to adjust the flow, since the coolant quickly redistributed itself downstream of the plate. This is due to the core's prismatic elements, which do not create isolated flow paths through the core. However, due to the flexibility afforded by the TCR's additively manufactured fuel elements, the channel geometry in each fuel assembly could be individually tuned so as to bias the coolant toward the center of the core.

The coolant channel gaps were altered in the four rings of the core as follows (starting with the inner ring): the gaps in the first ring were increased by 10%, the gaps in the second ring were unchanged, and the gaps in the third and fourth rings were decreased by 20% and 30%, respectively. With these adjustments, the radial temperature gradient was reduced to ~18°C, or ~84% less than the baseline case (see Fig. 6). The pressure loss through the core also increased to ~35 kPa, or ~35% higher than the baseline case. As with the baseline results, the predictions from the analytical and STAR-CCM+ models very closely match.

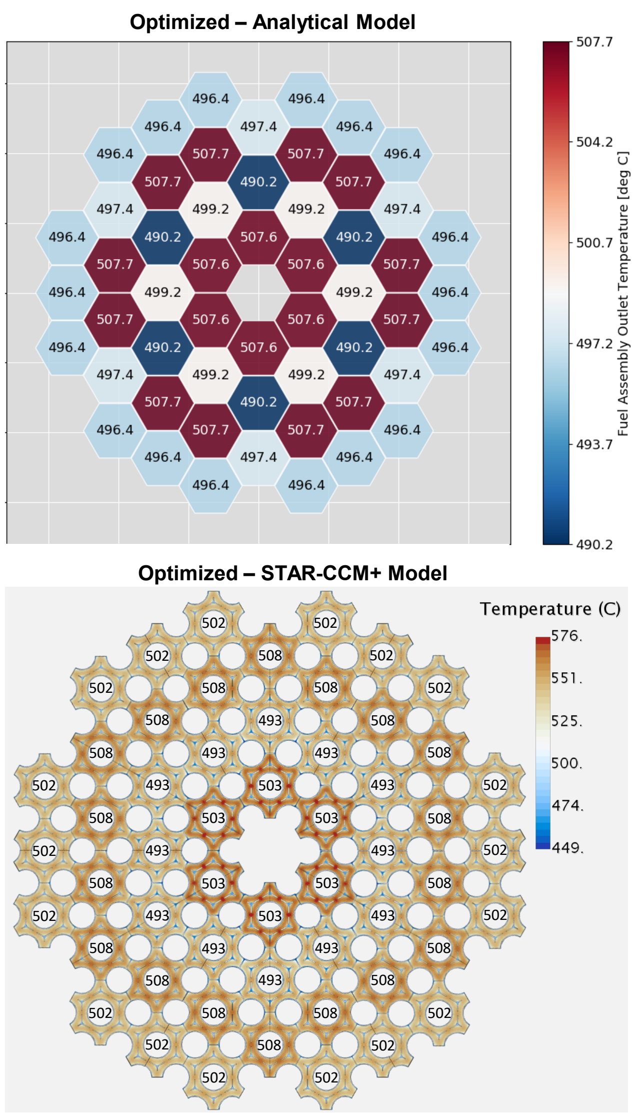

Fig. 6. Optimized case, average helium temperature at the outlet of each fuel assembly for the analytical (top) and STAR-CCM+ (bottom) models.

CONCLUSIONS

A twofold modeling approach was employed to explore options for flattening the radial temperature profile across the TCR core. These approaches included: a simple analytical model and a higher-fidelity numerical model in STAR-CCM+. Though the most attractive option initially for reducing the radial temperature gradient was to add an orifice plate above or below the core's fuel assemblies, the core's prismatic design negated the flow-biasing effects produced by the plate. However, utilizing the benefits of additive manufacturing by altering the channel geometry in each fuel assembly proved a viable method of reducing the radial temperature gradient by ~84% while increasing the pressure loss through the core by only ~35%. Additional optimization of the channel geometry could reduce the gradient even further, and alternative methods such as varying the surface roughness of the fuel elements or adding surface features instead of altering the channel gaps could be explored.

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