# Cooling Channel Optimization in Additively Manufactured Gas Cooled Reactor Core

Justin Weinmeister, Prashant Jain

*Oak Ridge National Laboratory, 1 Bethel Valley Rd, P.O. Box 2008, Oak Ridge, Tennessee 37831, weinmeistejr@ornl.gov*

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## INTRODUCTION[1]

New designs for nuclear reactors are now able to take advantage of advanced manufacturing technologies and materials which provide a greater design space for optimization. The Transformational Challenge Reactor (TCR)[2] is designed to demonstrate the revolutionary changes these developments bring to nuclear energy. Current TCR designs are based around a 3 MWth gas-cooled reactor which uses a mixture of traditionally and additively manufactured core components to offer an inherently safe core in a compact size. The TCR fuel forms are manufactured using conventionally fabricated uranium nitride tristructural isotropic (UN TRISO) fuel particles [1] embedded inside an addictively manufactured silicon carbide (SiC) matrix [2]. The fuel forms are first additively manufactured using binderjet printing followed by chemical vapor infiltration [3]. This additively manufactured design is novel compared to previous high temperature gas reactors which heavily rely upon cylindrical cooling channels or pebble bed designs [4].

Unfortunately, engineering software does not yet permit open-ended geometry optimization for thermal fluidic analysis. However, the problem's mechanics give a few simple constraints that make the problem tractable without eliminating potentially useful designs. This work is focused on constricting the design for detailed optimization work to come while retaining the global optimum. This step is required for the TCR as no comparable design exists to baseline further optimization too. In this summary we first present the problem statement and constraints, then our analysis methods, and finally the results and conclusions of the early optimization work for cooling the TCR, a high temperature gas cooled reactor.

### Design Envelope

The current TCR design is an approximately 3 MWth demonstration reactor with an active core region under 1 m in height and width and a nominal fuel power density of 40 W/cc. This demonstration targets a compact and optimal core design. The active core region consists of fuel (UN TRISO in SiC), moderator (yttrium hydride), coolant (helium), and structural elements (316L stainless steel). The structural elements act as neutron poisons and their share of the core volume needs to be reduced as much as possible. The ratio of fuel to moderator depends upon final configuration, but neither has strict geometric restrictions on the core design.

While many theoretically possible designs exist for the TCR core, owing to the possibility of realizing complex geometries with additive manufacturing, the need to simplify construction, operations, and manufacturing makes a tessellating, stackable design the best choice. The TCR features a nominal repeating unit that is hexagonal in shape, potentially with unique Y-shaped fuel elements with integrated cooling. The fuel will be stacked around a central hexagonal moderator unit and tessellated across the entire area of the core. The Y-shaped elements may also be integrated into larger cog shaped elements. The fuel element's most basic motif is shown in Fig. 1 where dark grey is the fuel region and light grey is the coolant region.

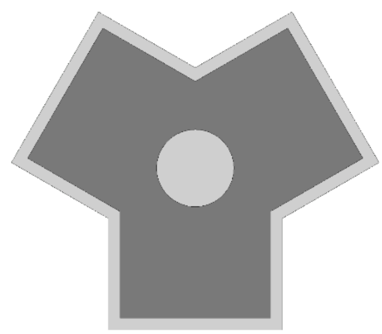

Fig. 1. A depiction of a nominal fuel element motif of the TCR.

### Methods

To determine the performance of the reactor, a baseline case was established to evaluate the performance of alternatives. Thermal fluidic analysis was carried out in Siemens' Simcenter STAR-CCM+ on a single repeating unit for the entire core height based on the 3 MWth specification with an inlet temperature of 300°C. The baseline simulation contains 0.1 m inlet and outlet plenums on a 1 m long core. The boundary conditions are a 1 psi total pressure inlet on top

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[2] Transformational Challenge Reactor: tcr.ornl.gov

with a zero pressure outlet on the bottom. The coolant is helium at 7 MPa. The performance of each design will be evaluated based on the maximum temperature seen in the fuel, flow resistance (measured by mass flow), and thermal gradients. Higher performing coolant designs will keep the fuel cooler while having less severe temperature gradients, reducing thermal stresses.

Before detailed optimization can be run on the geometry, the general distribution of coolant in and around the fuel must be determined for the various power levels seen in the reactor. To understand the design space nine simulations were run using three power levels and three coolant geometries. The three power levels were 30, 40, and 50 W/cc which represent low power, average power, and high power regions of the core, respectively. These values came from the average, low, and high power fuel assemblies seen in the reactor physics simulation of the proposed core design. The three coolant geometries were exterior cooling only, interior cooling only, and mixed cooling. For the interior and exterior cooling cases, the coolant areas were scaled to provide the same coolant cross-sectional area.

The geometry permitted a directed mesh approach with 1.3 million hexahedral cells while the coupled Reynolds-Average Navier-Stokes equations were solved for the flow. The realizable k-epsilon closure model was used with a turbulent Prandtl number of 0.9 and a two-layer wall formulation to model the turbulent conjugate heat transfer problem. The coolant was helium at 7 MPa with temperature dependent density, thermal conductivity, and specific heat. Heat generation was modeled as a constant volumetric heat source based on the provided power densities.

## VALIDATION

The solution's mesh independence was check for the mixed geometry case at 40 W/cc heat generation rate using a coarser mesh solution with half has many cells. The errors were 0.39% for the maximum fuel temperature, 0.40% for the maximum coolant temperature, 1.0% for the outlet coolant temperature, 3.0% for the average velocity, and 4.9% for the mass flow rate.

Figure 2 shows a comparison of the simulated heat transfer coefficient for the internal channel in the mixed geometry versus the predicted average heat transfer coefficient from the Dittus-Boelter equation. Table 1 lists the properties and values of the flow used to compute the average heat transfer coefficient. The Dittus-Boelter prediction of 2835 W/m$^2$·K is 5.9% higher than the average STAR-CCM+ value of 2667 W/m$^2$·K. This error is within the expected accuracy of 25% for the Dittus-Boelter equations [5]. These results lend validity to the preliminary model's accuracy, but they still need to be fully validated against experimental results prior to manufacture of the reactor.

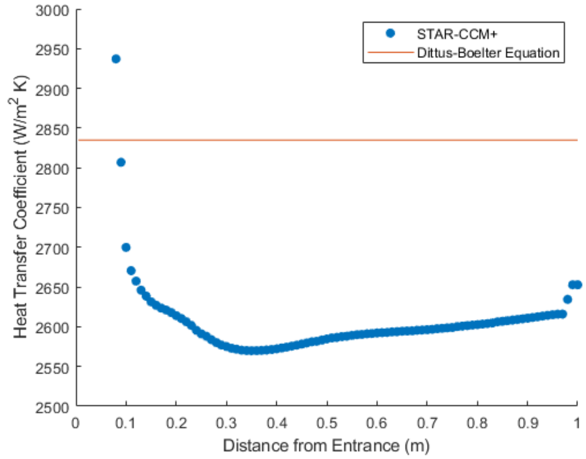

Fig. 2. Heat Transfer Coefficients in Internal Channel for Mixed Cooling Geometry

Table 1. Fluid and Heat Transfer Properties

| Property | Units | Value |
|---|---|---|
| Density | kg/s | 5.02 |
| Dynamic Viscosity | Pa·s | 3.48e-5 |
| Specific Heat | J/kg·K | 5188 |
| Thermal Conductivity | W/m·K | 0.275 |
| Length Scale | m | 0.008 |
| Velocity | m/s | 29.67 |
| Prandtl Number | | 0.656 |
| Reynolds Number | | 34,239 |
| Nusselt Number | | 82.4 |
| Heat Transfer Coefficient | W/m$^2$·K | 2,835 |

## RESULTS

Results from the nine baseline cases are tabulated in Table 2. The highest mass flow rates and lowest temperatures are seen in the mixed cooling geometry where the average case at 40 W/cc has a mass flow rate of 16.4x10$^{-3}$ kg/s with a maximum fuel temperature of 770 K. A cross-sectional view of the temperature is shown in Fig. 3 with the full geometry on the left and a zoomed view of the outlet on the right. The helium coolant enters the upper plenum at 573 K (300 C) before leaving the domain at approximately 700 K (430 C). A large portion of the coolant travels through the center cooling channel and experiences less heat transfer than the coolant on the perimeter of the geometry.

The external-only cooling showed very low mass flow rates in comparison to the geometries with internal cooling which resulted in high maximum fuel temperatures. Additionally, the internal-only cooling cases showed large temperature gradients at the exterior corners of the fuel which are susceptible to thermal stresses. The mixed cooling case showed lower thermal gradients than the other cases, but it still showed significant gradients in the large fuel meat sections on each leg of the Y-shape that can be reduced with final optimization. These gradients are shown in Fig. 4.

Table 2. Output Variables for Design Cases

| Geometry | Volumetric Heating (W/cc) | Mass Flow (kg/s) | Average Velocity (m/s) | Max Fuel Temperature (K) | Max Coolant Temperature (K) | Coolant Outlet Temperature (K) |
|---|---|---|---|---|---|---|
| Internal | 30 | 14.0e-3 | 26.2 | 782 | 747 | 705 |
| Internal | 40 | 13.6e-3 | 27.3 | 858 | 811 | 753 |
| Internal | 50 | 13.3e-3 | 28.3 | 939 | 878 | 804 |
| Mixed | 30 | 16.6e-3 | 19.3 | 718 | 708 | 663 |
| Mixed | 40 | 16.4e-3 | 19.9 | 770 | 756 | 694 |
| Mixed | 50 | 16.1e-3 | 20.4 | 823 | 804 | 727 |
| External | 30 | 6.7e-3 | 16.0 | 990 | 946 | 854 |
| External | 40 | 6.3e-3 | 17.1 | 1157 | 1095 | 970 |
| External | 50 | 5.9e-3 | 18.2 | 1341 | 1260 | 1101 |

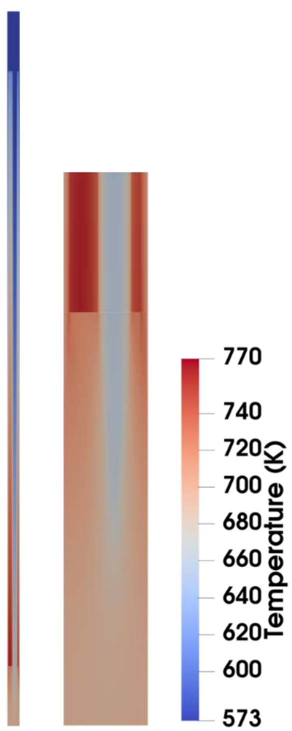

Fig. 3. Vertical Temperature Cross-section of Fuel and Coolant

Additionally, Fig. 5 plots the coolant and fuel temperatures versus the vertical position of the fuel element for the mixed geometry, 40 W/cc case. The coolant temperature reference is the center of internal cooling channel and the fuel reference is the maximum fuel temperature at that cross-section. The coolant does not begin warming for ten centimeters and only reaches a linear steady state around 40 centimeters into the core while the fuel reaches its linear region within 20 centimeters. Ultimately the large gap between the coolant and fuel temperatures, 113 K at the outlet, is representative of the large thermal gradients in the fuel element seen in Fig. 4.

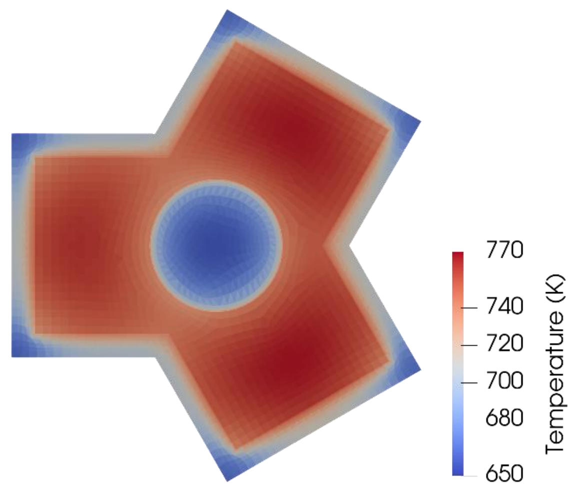

Fig. 4. Horizontal Temperature Cross-section of Fuel Element at Coolant Exit

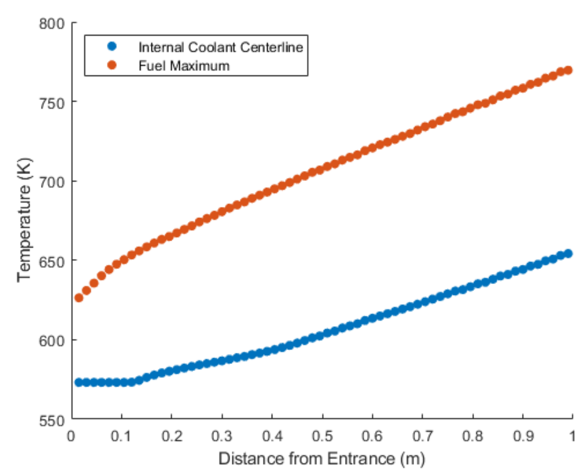

Fig. 5. Vertical Temperature Probes for Coolant and Fuel

## CONCLUSIONS

Additive manufacturing technology has allowed for the development of significantly improved cooling channel geometries in high temperature gas reactors due to the lower cost of adding complex features to the core geometry. These improvements improve the overall reactor design by improving heat distribution, reducing inlet and outlet complexity, and lowering pressure losses. Initial optimization studies for the TCR looked at reducing the allowable design space by investigating the general distribution of coolant around the fuel elements of the core.

These results showed that a mixed cooling geometry gives the best performance when looking at pressure drop and peak fuel temperatures despite not producing the highest turbulent fields or coolant wall distances. This mixed coolant geometry provides a baseline geometry to compare future detailed optimization studies too. Upcoming work is focused on taking these preliminary results and iteratively optimizing the individual channel shapes to provide the lowest fuel temperatures. Additional work will also look at finding the optimal ratio of internal and external coolant for the fuel element. Methods include surface features, non-traditional channel shapes, and helical coolant channels. This work has produced new high temperature gas cooled reactor core geometries which are able to operate at efficiencies not achievable with traditional materials and manufacturing methods.

## ACKNOWLEDGEMENTS

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