Ring Model Development and Validation for Prismatic HTGR Core Thermal-hydraulics and Safety Analysis

Nuclear Science and Engineering Division

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ABSTRACT

Because of the complex core geometry, prismatic high temperature gas-cooled reactors (prismatic HTGRs) often exhibit complex thermal fluid behaviors during both normal operating and transient conditions. Most HTGR designs rely on passive safety system for decay heat removal, such as the reactor cavity cooling system (RCCS). During postulated accidents like Pressurized Conduction Cooldown (PCC) event, the decay heat is first radially transferred from the core region to the reactor vessel outer surface, then to the RCCS cooling panels. The peak fuel temperature is controlled by heat transfer mechanisms with two distinctive characteristic length scales, i.e., the core-wise effective heat conduction and local heat conduction in the fuel pellet scale. As both length scales are essential to determine the fuel temperature, from the modeling perspective, computer codes must be able to capture heat transfer in both scales. This is challenging for both computational fluid dynamics (CFD) tools because of extremely large amount of computation resources required, and for system analysis codes because of the challenge to model the complex core geometry.

Under the support of DOE-NE's Nuclear Energy Advanced Modeling and Simulation (NEAMS) program, efforts have been pursued to support HTGR technology development and its modeling and simulation needs. There is a particular need for advanced modeling and simulation tools to predict thermal-fluid behavior during safety-related transients. In our previous studies, the ring model was adopted in SAM and further developed to simulate the normal operating condition and a PCC event using the MHTGR-350 design of General Atomics as the reference design. This current work represents a continuation of these previous efforts, and the focus is to critically review and examine simplifications and assumptions made to develop the ring model, and to perform code validation using experimental data from an integral-effect test facility, the High Temperature Test Facility (HTTF) at the Oregon State University. In this study, the test PG-27 from the HTTF test suite was selected for code validation purpose. The test PG-27 is a transient test designed to simulate the PCC event of the MHTGR design. Very good agreements between SAM prediction and experimental measurements were found in both coolant and solid structure temperatures during the transient.

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1 Introduction

Due to their high thermal efficiency, inherent safety, and potential to provide high-temperature process heat, high temperature gas-cooled reactor (HTGR¹) designs are among the advanced reactor concepts currently under consideration by the Gen-IV International Forum (GIF) [1] and have attracted worldwide interests. There are two types of HTGR designs, namely the pebble bed type (pebble bed HTGR) and the prismatic type (prismatic HTGR), depending on their fuel forms. Aside from the fuel form difference, both types of HTGR designs share many common technical basis, such as the use of TRISO fuel, graphite reflector, and helium coolant, having relatively low power density, and using reactor cavity cooling system (RCCS) for passive decay heat removal, etc.

Compared with light water reactor designs, because of the complexity in core geometries and the reliance on the RCCS for passive core cooling, HTGRs exhibit more complex thermal fluid behavior during both normal operating and transient conditions. As for most light water reactor designs that use fuel rods/bundles, the main core heat removal mechanism, i.e., convective heat transfer between the fuel rods and coolant, does not really change between the normal operating and transient conditions (such as the loss of coolant accidents). The only difference is where the coolant comes from (e.g., coolant pump driven vs. emergency core cooling system injection) and the switch from single-phase convective heat transfer to two-phase boiling heat transfer. For HTGR designs, between the normal operating and transient conditions, the main heat removal mechanism changes significantly.

For normal operating conditions, the main mechanism is predominantly local conjugate heat transfer between the fuel and the gas coolant. In the pebble bed design, heat is first conducted from pebble internal to its surface, then to the helium gas via convective heat transfer taking place at the pebble surface. In the prismatic design, heat is first conducted from fuel pellets to the surfaces of adjacent coolant channels, then to the coolant via convective heat transfer. In both cases, the heat transfers are dictated by local thermal fluid phenomena, and their characteristic lengths are rather small, i.e., in pebble bed designs, it is the pebble size; and in prismatic designs, it is the distance between a fuel pellet to its nearest coolant channel. The characteristic lengths of such localized heat transfers are in the order of centimeters, as schematically illustrated in Figure 1.1.

¹ Gen-IV International Forum (GIF) uses Very-High-Temperature Reactor (VHTR) for such reactor types. However, the original targeted core outlet temperature has been reduced from ~1000 °C to 700-950 °C, and thus, in this document, we will use HTGR to represent the general concept.

Figure 1.1. Local heat transfer phenomena: (left) pebble-to-fluid conjugate heat transfer in pebble bed HTGR, (right) pellet to coolant channel conjugate heat transfer.

One of the key postulated design basis accidents of HTGRs is the Pressurized Loss of Forced Cooling (PLOFC) or Pressurized Conduction Cooldown (PCC) event. During the postulated PCC event, following the loss of offsite power, the reactor scrams and forced cooling in the core is lost. Decay heat is primarily removed by the core-wise radial heat conduction and thermal radiation from the core region to the reactor vessel surface, and eventually to the reactor cavity cooling system via thermal radiation and convection. This core-wise radial heat transfer is sometimes termed as the effective heat conduction, and it controls the radial core temperature distribution in an averaged sense. Compared with the main heat removal mechanism under normal operating conditions, this core-wise effective heat conduction adds an additional length scale, corresponding to the reactor core diameter, in the order of meters, as illustrated in Figure 1.2. During the PCC event, both heat transfer mechanisms, i.e., core-wise effective heat conduction and heat conduction within fuel pebbles/fuel pellets, are important to determine the fuel temperature transient behavior. To accurately predict the peak fuel temperature during such transient events, it requires the simulation tools to capture the heat transfer in both length scales.

Figure 1.2. The core-wise heat transfer during HTGR transients, such as PCC.

For prismatic HTGRs, two popular methods for performing thermal analysis on prismatic HTGR cores include the unit-cell and CFD methods [2]. The unit-cell approach can be seen as a simplified and homogenized method that uses a unit cell to represent the averaged behavior

of a larger domain, such as a fuel assembly. As schematically shown in Figure 1.3a [3], a unit cell can be set up as coolant channel-centered, and the surrounding graphite matrix and adjacent fuel pins are rearranged into ring shapes, such that a local two-dimensional RZ geometry could be used. With multiple unit cells, this modeling approach can capture the core wise variation, such as power density distribution and fuel temperatures. The unit-cell approach is well suited for the simulations of both the normal operating condition and certain transients when the core-wise radial heat conduction is unimportant. For prismatic HTGR transients like the PCC event, the unit-cell approach lacks the capability to model the core-wise effective heat conduction, which should be addressed in a different way.

One the contrary, CFD methods can capture thermal fluid behaviors of different length scales, if they are adequately resolved by mesh. This, however, implies that the entire core must be meshed and modeled to capture both the localized and core-wise heat transfer. Such CFD simulations will require significant efforts in mesh generation and extremely large amount of computational resources, because of the complex core geometry and the long period of time of typical HTGR transients, in the order of 10 to 100 hours. For example, Figure 1.3b [4] shows the mesh of 1/12th hexagonal fuel block used to model core bypass flow phenomenon, and it is a clear indication that how expensive CFD can be to model the entire core. Instead, for prismatic HTGR applications, CFD methods are still limited in applications investigating localized thermal fluid phenomena, such as bypass flow, lower plenum flow mixing, upper plenum jet mixing, etc. A recent study [5] used porous medium approach and modeled 1/12 reactor core only to reduce the overall mesh size. For a long transient event such as PCC, it is still prohibitively expensive, and steady state CFD results were obtained at different decay heat levels, instead of the transient results for the entire PCC event.

Figure 1.3. The unit-cell approach [3] and CFD approach [4].

Based on the discussion above, it is clear that an intermediate-resolution modeling approach, between the full CFD and unit-cell model, is needed for the long simulation of prismatic HTGR transient events, such as PCC. Such intermediate-resolution methods must capture the heat transfer mechanisms in both the localized and core-wise length scales, and still be fast running. To achieve this goal, we follow the so-called ring model approach proposed by Strydom et al. [3]. The basic idea is to homogenize the core regions, including the inner and outer reflector regions and the active core region, and rearrange them into concentric rings, as illustrated in Figure 1.4. In this approach, the localized heat transfer is captured within the

homogenized core rings, and additional ring-to-ring radial heat conduction is used to capture the core-wise heat conduction.

Figure 1.4. MHTGR-350 core radial layout and the homogenized ring model [3].

Under the support of DOE-NE's Nuclear Energy Advanced Modeling and Simulation (NEAMS) program, efforts have been pursued to support HTGR technology development and its modeling and simulation needs. In a previous effort, the ring model was adopted and further developed using the SAM code to simulate the normal operating condition and a PCC event using the MHTGR-350 design of General Atomics as the reference design [6]. In this work, to further improve the model fidelity for the localized heat transfer, the fuel assembly level homogenization assumption was removed. Each ring of fuel assembly of the active core was represented by 11 coolant channels and 22 heat structures to conserve not only the solid structure volumes but also their representative thicknesses. Each coolant channel was located between two heat structure rings. The heat structure ring thickness was calculated based on the material volume to represent actual geometry dimensions. Hence, the active core (fuel assemblies) was simulated with 99 circular rings where 66 rings for homogenized fuel heat structure and 33 rings for gas coolant as shown in Figure 1.5. Under this configuration, each coolant channel communicates with its two adjacent heat structures to simulate the local conjugate heat transfer. Heat structure surfaces of adjacent rings were connected using gap heat transfer mechanism to capture the core-wise heat conduction. The model was successfully applied to simulate the normal operating condition and the PCC event of the MHTGR-350 design, and more details are provided in our previous report [6].

Figure 1.5. SAM ring model for MHTGR-350 simulation [6].

Following the SAM ring model development and its demonstration with the MHTGR PCC event, during last fiscal year, effort was taken to perform code validation of the ring model using experimental data from the scaled integral-effect test facility, the High Temperature Test Facility (HTTF) at the Oregon State University [7]. The test PG-26 was selected for the code validation purpose. However, due to very large uncertainties in the experimental procedures, large discrepancies were found between experiment measurements and model predictions, including both the SAM simulation under the NEAMS program support and RELAP5 simulation separately performed by INL researchers under the ART program support [8]. This current work is a continuation of the previous ring model development and code validation work. In this current study, the HTTF test PG-27 to simulate the PCC event, was selected for continuous code validation effort. Another focus of this study is to rigorously review and examine the simplifications and assumptions made to develop the ring model. This is deemed to be an essential component of the code validation work, as the ring model development involves homogenization and rearrangement, and thus length scale distortion may be introduced.

The rest of this report is organized as follows. Section 2 gives detailed descriptions on how ring model is applied to prismatic HTGR type of application and uses HTTF as example

application. Section 3 focuses on the ring model code validation using experimental data from the HTTF test PG-27, a dedicated test to simulate MHTGR PCC event. A summary of this work is presented in Section 4.

2 Ring Model Development

In order to apply the ring model to HTGR design and licensing, it is important to be able to predict the performance during normal operation and off-normal transients such as Depressurized Conduction Cooldown and Pressurized Conduction Cooldown events. As a first step, the model needs to be validated against experimental data that exhibit similar phenomena. Lessons learned from benchmarking exercises will help to identify shortcomings or limitations in the model and new methods or strategies will be investigated to improve the model. In this section, the development of 2D ring model for the High Temperature Test Facility (HTTF) is first presented, followed by a discussion on how such an approach is applied to MHTGR core design.

The HTTF [7] is an integral system test facility constructed and operated at the Oregon State University using General Atomic's MHTGR as its reference design. The main objective of this test facility is to experimentally investigate the system-level thermal fluids behavior of interest to MHTGR transients. Compared to the MGHTR, the HTTF is scaled $\frac{1}{4}$ in length and diameter and operated at prototypical temperature but at reduced pressure. The HTTF is primarily designed to model Depressurized Conduction Cooldown therefore the reduced pressure is not a factor. The major components include the reactor pressure vessel (RPV), steam generator, Reactor Cavity Simulation Tank (RCST), and a Reactor Cavity Cooling System (RCCS). The primary loop consists of the reactor vessel, the heated ceramic core, steam generator, gas blower, and connecting pipes. The RCST simulates the environment outside the MGHTR following the loss-of-flow accident. The RCCS consists of water-cooled panels that surround the RPV to establish boundary conditions and control radiation heat transfer from the RPV wall.

The core is made up of Greencast 94-F ceramic blocks, shown in Figure 2.1a. Similar to MHTGR core configuration, the HTTF core is comprised of a central reflector, heated core, and side reflector. The heated core is loosely divided into three regions: inner, middle, and outer in the nomenclature used in this report. A permanent reflector made of silicon carbide surrounds the ceramic blocks. In the axial direction, the blocks are stacked upon one another as shown in Figure 2.1b to model the lower reflector, core, and upper reflector. Also illustrated in Figure 2.1a are 516 coolant channels (blue, green, and grey circles) cast within the ceramic blocks through which helium coolant flows through to remove heat. In addition, there are 6 coolant channels in the central reflector and 36 coolant channels (open circles) in the side reflector to model bypass flow in a prototypical reactor. The core is electrically heated using graphite heater rods. There are 210 heater rods (orange circles in Fig 2.1a) arranged in 10 heater banks with 3 heater legs per bank. The HTTF has over 400 data acquisition channels for thermocouples, pressure transducers, and gas sensors which are strategically placed in the primary, secondary, and tertiary sectors.

In the SAM 2D ring model, all components including the ceramic matrix, graphite heaters, coolant channels, core barrel, pressure vessel, and RCCS are modeled as concentric cylindrical rings. In the core, the heat transfer pathway is represented by the sequence heater ring – ceramic ring – coolant ring – ceramic ring – heater ring, etc. The methodology for constructing the ring model for the HTTF is described below.

Figure 2.1. (a) Core blocks, (b) Axial block stack [7].

2.1 Geometry conversion

Because the shape of core blocks is hexagonal and the coolant holes as well as heater rods are arranged in hexagonal pattern, the first step is to convert a hexagonal row into an equivalent annular ring and determine its radius in the ring model (Figure 2.2). The conversion is based on conservation of cross-sectional area encompassed by the hexagonal row, i.e.,

$$2\sqrt{3}f^2 = \pi r^2$$

$$r \approx 1.05f$$

Figure 2.2. Conversion from hexagonal geometry to ring geometry.

2.2 Coolant rings

Each core block is cast with 558 coolant channels of different sizes, comprising of 6 channels arranged in 1 hexagonal row in the central reflector, 526 channels arranged in 11

hexagonal rows in the heated region, and 36 channels (1 hexagonal row) in the side reflector. Most of the channels are 1.6-cm in diameter. The permanent reflector is not actively cooled. Each hexagonal row is converted into a ring as stated in 2.1.

For each coolant ring with inner radius r_i , the outer radius r_o is determined to conserve total flow area A of the individual coolant channels (area a_j) on the hexagonal row. Therefore,

$$A = \sum_j a_j$$

$$r_o = \sqrt{r_i^2 + \frac{A}{\pi}}$$

In the SAM model, a coolant ring is modeled as a one-dimensional fluid component (*PBOneDFluidComponent*) and the needed inputs are the radial coordinate, flow area, and hydraulic diameter which is calculated based on physical coolant channel geometry

$$D_h = \frac{4A}{P}$$

where P is the total perimeter of the coolant holes.

2.3 Heater rings

There are 210 channels (2.5-cm in diameter) cast into each core block to house the graphite heater rods which are smaller than the hole diameter to accommodate material expansion. The gap is filled with stagnant helium. Heat is radiated from the rods to the ceramic via the helium gap. The heaters are arranged in 9 hexagonal rows (shown in red circles in Figure 2.1a) which are converted to annular rings. A heater ring is modeled as a heat structure with 1-mm He gap on each side of the heat structure. Ring thickness is determined to conserve heater channel cross-sectional area.

Because heater channels are co-located with coolant channels on the same hexagonal rows, they need to be repositioned in the 2D ring model. An obvious choice is to shift each hexagonal row to its left or its right from the original location. However, it was quickly discovered that such artificial repositioning (~ 1 cm shift) creates distortion in the heating profile and leads to erroneous heat transfer characteristic in the core (see insert in Figure 2.4).

To correctly model heat transfer in the core, it is insightful to interpret how a heater rod passes heat to its neighboring coolant channels. As illustrated schematically in Figure 3.3, a heater rod is surrounded by 6 coolant channels and so each coolant channel receives $1/6^{\text{th}}$ the heat originating from the rod. The 6 coolant channels can be of the same size (large) or different sizes (large, medium, small in Figure 2.1a). On a different perspective, a large coolant channel is surrounded by three heater rods, a medium coolant channel “sees” two heater rods, and a

small coolant channel receives heat originates from just one rod. The goal of using different coolant channel sizes in HTTF is to obtain approximately uniform power-to-flow in the coolant channels and thus uniform coolant exit temperature. Therefore, in this arrangement a large coolant channel receives heat equal to the heat produced by 1/2 of a heater rod, a medium coolant channel receives heat from 1/3 of a rod, and a small coolant channel receives heat from 1/6th of a rod. Table 2.1 lists the quantity and size of coolant channels represented in the 11 coolant rings and the equivalent number of heater rods that transfer heat to them. The coloring scheme for denoting the coolant channels loosely divides them into three core regions, inner, middle, and outer.

Figure 2.3. Illustration of heat flow and removal in HTTF core blocks.

Table 2.1. Coolant channels and heat removal capacity in 11 coolant rings.

Coolant ring	Small channel	Medium channel	Large channel	Heat transfer from this # of rods
C1	24	6	0	6
C2	0	24	6	11
C3	0	0	36	18
C4	0	0	42	21
C5	0	0	42	21
C6	0	0	48	24
C7	0	0	54	27
C8	0	6	48	26
C9	0	12	48	28
C10	12	48	0	18
C11	60	0	0	10

The 210 heater rods which reside on nine hexagonal rows are redistributed into ten heater rings so that they provide heat to the 11 coolant rings to match the intended functional heat removal capability as listed in Table 2.1. Each heater ring is centered between two coolant rings and heat is distributed evenly to its two neighboring coolant rings. For example, heater ring H1 between coolant rings C1 and C2 should have 12 rods so that 6 rods are distributed to C1 and 6 rods to C2. Then to have 11 rods total for C2, H2 should have 10 rods so that 5 of them are distributed to C2. Based on this accounting method, Table 2.2 lists the assignment of heater rods to all ten heater rings. Because the number of rods assigned to C9 and C10 do not agree with those in Table 2.1, this can be corrected by not centering H9 between C9 and C10. Instead, H9 is moved closer to C9 to increase heat flow to C9 and less to C10.

Table 2.2. Coolant and heater rings with heat redistribution from heater to coolant.

Coolant ring ID	Heater ring ID	# of rods	Heat transferred from this # of rods
C1			6
	H1	12	
C2			11
	H2	10	
C3			18
	H3	26	
C4			21
	H4	16	
C5			21
	H5	26	
C6			24
	H6	22	
C7			27
	H7	32	
C8			26
	H8	20	
C9			23
	H9	26	
C10			23
	H10	20	
C11			10

The radial location and thickness of each heater ring can be determined as described herein. Consider a set of 3 rings with a middle heater ring M, a left coolant ring L, and a right coolant ring R, and disregard the existence of ceramic rings for now (they are the subject of the next section and do not affect the determination of location and thickness of the heater rings). The inner and outer radii of coolant rings are already known from the previous steps. Let A be total cross-sectional area of the heater rods assigned to heater ring M; r_{oL} be the outer radius of coolant ring L; r_{iR} be the inner radius of coolant ring R; and define

$$r_m = 0.5(r_{oL} + r_{iR})$$

the half-thickness δ of heater ring M can be found from

$$\pi[(r_m + \delta)^2 - (r_m - \delta)^2] = A$$

or

$$\delta = \frac{A}{4\pi r_m}$$

The inner and outer radii of heater ring M are then

$$r_{iM} = r_m - \delta$$

$$r_{oM} = r_m + \delta$$

With this method for modeling the nine heater rows using ten heater rings, the coolant exit temperature is expected to be quite uniform across the heated core as it is designed to be. Figure 2.4 shows the SAM results for steady-state condition at full power. The symbols indicate the coolant channels. The insert in Figure 2.4 shows a skewed and incorrect temperature profile if the nine heater rows are simply shifted to the right of the coolant rows and modeled using nine heater rings.

Figure 2.4. Steady state helium exit temperature in the coolant rings.

2.4 Ceramic rings

In the HTTF core, heat is radiated from heater rods to ceramic and then removed by helium flowing through the coolant channels. In the 2D ring model, this heat transfer pathway is represented by the sequence heater ring – ceramic ring – coolant ring – ceramic ring – heater ring, etc.

After determining the radial locations and thicknesses of all coolant and heater rings, then the locations and thicknesses of ceramic rings fall into place naturally according to the heat flow sequence. The total ceramic cross-sectional area represented by the rings is automatically conserved after having conserved coolant and heater cross-sectional areas. For example, using the notation in step 3.1.3 for a set of rings going from left to right: coolant ring L, ceramic ring 1, heater ring M, ceramic ring 2, coolant ring R. The inner and outer radii of coolant rings L and R are determined according to step 3.1.2. The inner and outer radii of heater ring M are determined according to step 3.1.3. Then the inner and outer radii of ceramic ring 1 are simply

$$r_{i1} = r_{oL}$$

$$r_{o1} = r_{iM}$$

The inner and outer radii of ceramic ring 2 are

$$r_{i2} = r_{oM}$$

$$r_{o2} = r_{iR}$$

There are 25 ceramic rings comprising of 2 in the inner reflector, 20 in the heated core, 2 in the side reflector, and 1 for the permanent reflector. The inner radius of the innermost central reflector ring is the center of the block. The outer radius of the second side reflector ring, and radii of the permanent reflector ring are determined by their physical boundary. The rest of the ring radii are determined according to the method described in this section.

2.5 Heat transfer area adjustment

In converting to a ring, the cross-sectional area (and hence volume) of coolant channels is conserved by the ring thickness. However, the physical perimeter (i.e., heat transfer surface area) of coolant channels does not equal the ring perimeter, and this will introduce incorrect heat transfer between ceramic and coolant. To correct this mismatch and to ensure that the actual heat transfer area between coolant channels and ceramic is properly accounted for in the ring model, it is necessary to apply an adjustment factor in the ceramic ring, defined as

$$HT_area_multiplier = \text{physical coolant channels perimeter} / \text{coolant ring perimeter}$$

One half of *HT_area_multiplier* is applied to the inner radius and the other half to the outer radius of a ceramic ring with variables *HT_area_multiplier_left* and *HT_area_multiplier_right*.

2.6 Surface coupling

Each heater ring and coolant ring is bounded by two ceramic rings (left and right) and to ensure temperature continuity in the ceramic matrix, which is physically true, the outer surface of the left ceramic ring is thermally coupled to the inner surface of the right ceramic ring. This is accomplished by the “*SurfaceCoupling*” component in SAM using a very large heat transfer coefficient. Similarly, the upper reflector and the top core block are coupled in the axial direction, as are the bottom core block and the bottom reflector.

2.7 Core barrel, upcomer and reactor pressure vessel

These three rings model the true physical layout, so no geometry conversion or adjustment of heat transfer area is needed. The upcomer is modeled as a coolant ring bounded by two structure rings: the core barrel on the left and the reactor vessel on the right. Radiative heat transfer between the core barrel and the vessel is accounted for in the model.

2.8 RCCS

The RCCS in the HTTF is not a scaled prototype of the RCCS system for MHTGR. It consists of a series of fiberglass panels cooled by water to set the boundary condition for the reactor. The RCCS is modeled with 2 rings: a structure ring for radiant heat transfer from the reactor pressure vessel and it is coupled to a water coolant ring for heat removal.

2.9 Ceramic effective thermal conductivity

The heat transfer characteristics in the core blocks is complicated by the presence of hundreds of holes cast into them, especially in key HTGR transients when radial heat transport is the dominant heat transfer mode. Because of these complexities, an effective thermal conductivity (ETC) for the ceramic is needed to properly model the reactor core thermal behavior in a system-level code like SAM. Previous work has relied on CFD analysis to deduce the ETC [9,10] for a particular core configuration. In the scope of the present work, the ETC is chosen by calibrating the HTTF temperature measurement in the ceramic at one location. Based on this method of calibration, it was determined that the ETC is about 34% the nominal value of the ceramic material.

3 HTTF Benchmark

The 2D ring model has been benchmarked against a Depressurized Conduction Cooldown test (PG-26) which was the first major test carried out in the HTTF [8,11]. The model has since been improved to incorporate new strategy in modeling heater rings and using effective thermal conductivity for ceramic. The improved ring model is validated with data from Test PG-27, a Pressurized Conduction Cooldown test.

3.1 Test PG-27

In MHTGR, a Pressurized Conduction Cooldown (PCC) event is characterized by the loss of forced flow, but the pressure boundary of the reactor remains intact. The reactor scrams, and decay heat is transferred to the surface of the reactor vessel by natural convection, conduction and thermal radiation inside the vessel; and eventually to the RCCS by thermal radiation and natural convection outside the vessel. Test PG-27 [12] was carried out to examine the progression of PCC in an integral test facility; and to provide data for benchmarking system codes.

In the test PG-27, two heater banks (banks 102 and 108) were operated that powered 42 heater rods to deliver up to 72 kW. The electric circuits that connect active rods form a zig-zag pattern as shown in Figure 3.1a. The heatup process took about 50 hours to establish quasi steady-state condition. Transient power, shown in figure 3.1b, was scaled to simulate decay heat in MHTGR and started in the ~69th hour. At the start of transient, all pumps and gas circulator were secured, and the flow rate was zero in each fluid in the system. The test was terminated in the 4th hour of transient due to loss of heater insulation.

Figure 3.1. (a) Core block with 2 heater banks activated, (b) Input power throughout the entire test [12].

3.2 Model assumptions

Besides the modeling strategies described in section 2.0, there are additional assumptions in the SAM model for test PG-27:

- (a) Steady-state conditions are assumed prior to PCC transient. Figure 3.2 displays the SAM results for steady-state temperature profile in the ceramic. Temperature increases in the direction of flow from top to bottom and thermal conduction to the unheated lower reflector raises the temperature there substantially as well. The inner core where it is unheated is several hundred degrees cooler than the heated region.

Figure 3.2. Temperature profile in Test PG-27 prior to PCC.

- (b) By nature of the 2D ring model there is no variation in the azimuthal direction. This assumption is not entirely valid because only 2 of the 10 heater banks were activated.
- (c) Because helium coolant flow rate is not measured in this facility, it is estimated as 0.09 kg/s prior to PCC based on input power and helium temperatures measured at the cross over duct (Figure 3.3) which is a concentric pipe that contains the hot leg from lower plenum and cold leg entrance to the reactor pressure vessel. Another possible technique to estimate the flow rate is to use data from the gas blower speed, back pressure and the blower performance map. However, this technique does not yield consistent results when applied to different tests such as Test PG-27 versus Test PG-26 [11].

Figure 3.3. Temperature in hot leg:TF-3102, and cold leg:TF-6101 & TF-6102.

- (d) A reduced effective thermal conductivity for the ceramic is used to account for the complex heat flow in the presence of hundreds of coolant holes and heater channels. The effective thermal conductivity of ~34% the nominal value is determined by calibrating the SAM results to the measured temperature in ceramic at 1 location. Figure 3.4 shows the steady-state axial temperature distribution in ceramic located in the outer core region. The x-axis starts from the bottom of block 1 and extends to the top of block 10. The single location chosen for calibrating the effective thermal conductivity is indicated in the figure.

Figure 3.4. Steady-state axial temperature distribution in ceramic in the outer core.

3.3 Thermocouples used for comparison with SAM results

The test data used for comparison with SAM predictions come from three different sectors: primary, secondary, and tertiary as depicted in Figure 2.1a. The instruments in the secondary and tertiary sectors are placed in locations that are considered equivalent to locations in the primary sector and are intended to serve as backup for instruments in the primary sector. Ideally, measurements would show little variation among these three sectors, but as will be seen later such is not the case. Many factors could have contributed to differences among instruments in different sectors such as misalignment and/or shifting of the core blocks, non-symmetric characteristics of the experiment, random and systematic standard uncertainties, data acquisition uncertainty, instrument alignment, and instrument location uncertainty [13]. Table 3.1 lists the names of available thermocouples in all three sectors in the heated core (inner, middle, outer) and the corresponding SAM variables. They are used in legends in comparison plots presented later.

3.4 Transient results

The SAM simulation of Test PG-27 does not include the long heat-up period prior to reaching steady state. Instead, the simulation is comprised of two steps: step 1 seeks a steady-state solution at constant power and flow rate to establish initial conditions; step 2 is a restart of step 1 to initiate a PCC transient. To compare with test data directly, SAM simulation makes use of the same time scale as in the experiment, so transient is initiated at $t=249000$ s and the comparisons start from $t = 200000$ s which includes the steady-state portion.

Table 3.1. Naming of thermocouples and corresponding SAM variables.

	Ceramic TS-nnnn			Helium TF-nnnn		
	inner	middle	outer	inner	middle	outer
Block 1:						
sector 1	1109	1111	1113	1110	1112	1114
sector 2	-	1124	-	1123	1125	-
sector 3	-	-	-	-	-	-
SAM	R15_bk1	R25_bk1	R35_bk1	R16_bk1	R28_bk1	R36_bk1
Block 3:						
sector 1	1303	1305	1307	-	1306	1308
sector 2	1317	1319	1321	1318	1320	1322
sector 3	1331	1333	-	1332	1334	1336
SAM	R15_bk3	R25_bk3	R35_bk3	R16_bk3	R28_bk3	R36_bk3
Block 5:						
sector 1	1503	1505	1507	1504	1506	1508
sector 2	1517	1519	1521	1518	1520	-
sector 3	1531	1533	1535	1532	1534	1536
SAM	R15_bk5	R25_bk5	R35_bk5	R16_bk5	R28_bk5	R36_bk5
Block 7:						
sector 1	1703	1705	1707	1704	-	1708
sector 2	1717	1719	-	1718	-	-
sector 3	1731	1733	1735	1732	1734	1736
SAM	R15_bk7	R25_bk7	R35_bk7	R16_bk7	R28_bk7	R36_bk7
Block 9:						
sector 1	1903	1905	1907	1904	1906	1908
sector 2	1917	1919	1921	1918	-	1922
sector 3	-	-	-	-	-	-
SAM	R15_bk9	R25_bk9	R35_bk9	R16_bk9	R28_bk9	R36_bk9

3.4.1 Natural circulation

After forced flow is terminated, natural circulation is established in the core. Figure 3.5 displays the helium velocity in various regions. Negative velocity indicates normal downward flow while positive velocity indicates reversed upward flow. In the central reflector and inner core, the flow remains in downward direction throughout the transient. The flow reverses direction briefly in the side reflector but quickly returns to downward flow. In the middle and outer core regions where the ceramic is at higher temperature than its surroundings, the flow reverses direction upward. In short, closed natural circulation loops are formed with upward flow in the middle part of the blocks and downward flow in the inner and outer parts. It is worth noting that natural flow velocity is very small, about two to three orders of magnitude lower than steady-state flow velocity. Therefore, it may be concluded that the dominant heat transfer mechanisms in PCC are thermal conduction and radiation, but not convection.

Figure 3.5. Calculated helium velocity in various parts of the core during PCC transient.

3.4.2 Outer core temperature

Figures 3.6 and 3.7 show the outer core helium and ceramic temperatures recorded in 5 axial blocks, respectively. In each figure there are up to 3 solid curves which are test data measured in different sectors: primary sector is shown in orange, secondary sector is shown in grey, and tertiary sector is shown in yellow. The dashed curve is SAM simulation results.

In the steady-state portion, temperature is lowest in block 9 and highest in block 1 because helium flows from top to bottom. Simulations agree reasonably well with test data, and both show higher temperature in ceramic than in helium in blocks 1, 3, 5, 7. While the same holds true in simulation results for block 9, test data in ceramic is lower than helium temperature. This is likely caused by more heat conducted to the lower plenum which has many support columns.

At the start of transient, temperature rises due to a ramp up in input power then falls when power decreases. In block 1 the observed initial rise is substantially less than predicted as well as less than observed in upper blocks, this again could be due to more heat being conducted to the lower reflector, plenum, and support material. In other blocks, the SAM predictions agree reasonably well with experiment, within the variation of measurements in different sectors. The rise and fall behaviors in helium and ceramic temperatures are well captured by SAM. It is further observed that temperatures recorded in the secondary sector tend to be lower than those

in the primary and tertiary sectors. The sources or causes for this deviation require further investigation.

Figure 3.6. Helium temperature in outer core in 5 axial blocks: solid curves are test data and dashed curve is SAM simulation.

Figure 3.7. Ceramic temperature in outer core in 5 axial blocks: solid curves are test data and dashed curve is SAM simulation.

3.4.3 Middle core temperature

Figures 3.8 and 3.9 show the outer core helium and ceramic temperatures, respectively. Like the outer core, temperature rise in block 1 at the start of transient is likely influenced by conduction to the lower plenum region and support structure. The observed peak temperature in block 1 is ~200 K lower than the peak in block 3 despite having higher temperature prior to PCC. Test data for helium temperature in block 5 shows significant deviation among the sectors,

>300 K difference between the primary and secondary sectors, an anomaly not observed elsewhere. On the other hand, in the same block the ceramic temperature in the secondary and tertiary sectors are equal, as are the temperatures in block 9. As can be inferred from all the data observed in the outer and middle core, deviation between sectors appear to be random and this underscores the need to present all available data when making comparison with code simulations.

Figure 3.8. Helium temperature in middle core in 5 axial blocks: solid curves are test data and dashed curve is SAM simulation.

As in the outer core, the rise and decay of temperature are well captured by SAM, indicating that the thermal conduction and radiation models perform as expected, and that the use of an effective thermal conductivity is needed when modeling a complex geometry with a system thermal hydraulic code. Overall, SAM results for the middle core are also in reasonably good agreement with test data within the range of variation recorded in three different sectors.

Figure 3.9. Ceramic temperature in middle core in 5 axial blocks: solid curves are test data and dashed curve is SAM simulation.

3.4.4 Inner core temperature

Figures 3.10 and 3.11 show the inner core helium and ceramic temperatures, respectively. Because there are no active heaters in the inner core, temperature is significantly lower than in the middle and outer core. There is also significantly less deviation in recorded temperatures among the sectors. In fact, almost identical measurements from different sectors are observed in several blocks, which is not seen in the middle and outer core. SAM predictions for the steady-state ceramic temperatures are in excellent agreement with experiment while the peak temperatures are consistently lower than test data.

Figure 3.10. Helium temperature in inner core in 5 axial blocks: solid curves are test data and dashed curve is SAM simulation.

Figure 3.11. Ceramic temperature in inner core in 5 axial blocks: solid curves are test data and dashed curve is SAM simulation.

4 Summary

Prismatic HTGRs often exhibit complex thermal fluid behaviors during normal operating and transient conditions. Because of the multi-scale heat transfer mechanisms involved in prismatic HTGR transients, such as PCC, it is a challenging task to model HTGR transient using system analysis codes. Under the support of DOE-NE's Nuclear Energy Advanced Modeling and Simulation (NEAMS) program, efforts have been pursued to support HTGR technology development and its modeling and simulation needs. Under this task, the ring model approach has been adopted in SAM and further developed to simulate prismatic HTGR transient. In this study, we performed critical reviews on the simplifications and assumptions made to develop the ring model. We described a step-by-step process for constructing a ring model for the HTTF. The same process can be applied or extended to HTGR in general. Following that, a code validation study was performed using experimental data from HTTF's test PG-27, a test case to simulate PCC event of MHTGR. For both fluid and solid structure temperature during the entire transient, SAM-predicted values agree well with experimental measurements. In the future, to further assess the validity and uncertainty introduced into the 2D ring model because of geometry simplifications, it is planned to compare the 2D ring model simulation results with fully resolved 3D model for both steady-state and transient conditions.

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