Simulations of the High Temperature Test Facility using SAM

Nuclear Science and Engineering Division

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ABSTRACT

Under the support from the U.S. Department of Energy Office of Nuclear Energy's Nuclear Energy Advanced Modeling and Simulation (NEAMS) program, an effort is being pursued to support the modeling and simulation needs of high-temperature gas-cooled reactor (HTGR) technology development. There is a particular need for advanced modeling and simulation methods and tools to predict thermal-fluid behavior in the nuclear reactor primary system during safety-related transients. This report focuses on one such activity related to HTGR: developing a model of the High Temperature Test Facility (HTTF) at Oregon State University using the system-level code SAM, and using the model to understand thermal response behavior in the facility. Note this activity is coordinated with the DOE-NE's Advanced Reactor Technology Gas-Cooled Reactor Program. Specifically, this work encompasses three main activities in FY20:

- 1) SAM Model Development for HTTF – Develop a SAM input file based on a ring model approach. In this approach, all components including the ceramic, heaters, coolant channels, core barrel, upcomer, pressure vessel, and Reactor Cavity Cooling System (RCCS) are modeled as concentric cylindrical rings. A primary advantage of the ring model is in its ability to account for radial heat transport (via conduction and radiation) which is the dominant heat transfer mode in HTGR transients. As a first step to verify the validity of the model, steady state calculations were compared with results obtained from the RELAP5-3D code and a commercial computational fluid dynamics (CFD) code STAR-CCM+.
- 2) Analysis of Pressurized Conduction Cooldown (PCC) – Utilizing the SAM model to simulate a PCC transient in which core flow transitions from forced flow to natural circulation, and the facility cools down at the operating pressure. Heat is conducted radially to the pressure vessel and then radiated to the water-cooled RCCS.
- 3) Simulation of Depressurized Conduction Cooldown Test PG-26 – Utilizing the SAM model to simulate the first major test in the HTTF – Test PG-26. Due to unexpected operation challenges encountered in this test, it was not feasible to benchmark SAM results with test data. Rather, this activity lays the groundwork for familiarity with instrument placement, data collection and processing that will facilitate future benchmarking activities.

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1 Introduction

The High Temperature Test Facility (HTTF) at Oregon State University was designed to examine the performance of High Temperature Gas-Cooled Reactors (HTGRs) during steady-state and transient operations [1]. The test facility was designed using the Modular High Temperature Gas-Cooled Reactor (MHTGR) [2] as its reference design, and the primary goal of the tests was to understand thermal hydraulic behavior during the Depressurized Conduction Cooldown (DCC) event [1]. It also has the potential to perform limited tests to gain understanding of the progression of the Pressurized Conduction Cooldown (PCC) event, and other phenomenon of interests during normal operations [1]. Additionally, the HTTF can provide valuable test data for benchmarking computer tools and models that are needed to support HTGR technology development and licensing.

The System Analysis Module (SAM) [3] computer code is being developed under the NEAMS program, and the US NRC has formally stated its intent to use the SAM code for advanced non-LWR design basis event analysis [4]. Previously, SAM has been used to model the thermal hydraulic behavior in the General Atomic's MHTGR design [5]. The test campaign at HTTF provides a valuable opportunity to utilize SAM to model an integral effect facility and to assess and improve its modeling approach – the ring model – of a prismatic block core MHTGR design.

This report is organized as follow. Section 2 provides a brief description of the HTTF. Section 3 describes the modeling approach of the HTTF using SAM. Section 4 presents steady state calculations for full operating power and compares them with results obtained from the RELAP5-3D code and STAR-CCM+ [6][7][8][9]. Section 5 presents results for a Pressurized Conduction Cooldown transient scenario. Section 6 discusses SAM's simulation of a Depressurized Conduction Cooldown test, Test PG-26, conducted at the HTTF. Lastly, Section 7 summarizes the key takeaways and suggests future follow-up work.

2 Description of the High Temperature Test Facility

The HTTF is an integral helium-cooled test facility (Figure 2.1) located at Oregon State University. It was based on General Atomic's Modular High-Temperature Gas-Cooled Reactor (MHTGR) design which uses prismatic graphite blocks in the core and reflectors. Compared to the MHTGR, the HTTF was scaled $\frac{1}{4}$ in length and diameter and operated at prototypical temperature but at reduced pressure. The HTTF was primarily designed to model Depressurized Conduction Cooldown therefore the reduced pressure is not a factor. The major components (Figure 2.1) 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 MHTGR 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 comprises of Greencast 94-F ceramic blocks, shown in Figure 2.2, which encompass radial regions known as the central reflector, the heated core, and side reflector. The heated core is further divided into three regions: inner, middle, and outer in the nomenclature used in this report. A permanent reflector, also shown in Figure 2.2, made of silicon carbide surrounds the ceramic blocks. In the axial direction, the blocks are stacked upon one another as shown in Figure 2.3 to model the lower reflector, core, and upper reflector. There are 516 coolant channels cast within the ceramic blocks through which helium coolant flows to remove heat in the heated core region. In addition, there are 6 coolant channels in the central reflector and 36 coolant channels in the side reflector to model bypass flow in a prototypical reactor.

The HTTF has over 400 data acquisition channels for thermocouples, pressure transducers, and gas sensors. The core is electrically heated using graphite heater rods. There are 210 heater rods arranged in 10 heater banks with 3 heater legs per bank to deliver 2.2 MW heating power. In its current configuration, 4 of 10 heater banks were utilized with maximum power output of 880 kW.

Figure 2.1 Reactor Pressure Vessel and Reactor Cavity Storage Tank (left) [10], and Reactor Cavity Cooling System (right) [1]

Figure 2.2 Core ceramic block (left) and permanent reflector (right) [1]

Upper Core Reflector HTTF-415110	Upper Reflector #2 HTTF-415105	Upper Core Reflector HTTF-415110
	Upper Reflector #1 HTTF-415104	
	Core Block #10 HTTF-415202	
Center Core Reflector HTTF-415109	Core Block #9 HTTF-415201	Center Core Reflector HTTF-415109
	Core Block #8 HTTF-415201	
Center Core Reflector HTTF-415109	Core Block #7 HTTF-415201	Center Core Reflector HTTF-415109
	Core Block #6 HTTF-415201	
Center Core Reflector HTTF-415109	Core Block #5 HTTF-415201	Center Core Reflector HTTF-415109
	Core Block #4 HTTF-415201	
Lower Core Reflector HTTF-415108	Core Block #3 HTTF-415201	Lower Core Reflector HTTF-415108
	Core Block #2 HTTF-415201	
	Core Block #1 HTTF-415201	
HTTF-415107	Lower Reflector #3 HTTF-415103	HTTF-415107
HTTF-414034	Lower Reflector #2 HTTF-415102	Lower Core Reflector HTTF-415108
	Lower Reflector #1 HTTF-415101	
Lower Plenum Rear Reflector HTTF-414033	Lower Plenum Roof HTTF-414032	Lower Plenum Outlet Reflector HTTF-414035
	Lower Plenum	
	Lower Plenum Floor HTTF-414031	

Figure 2.3 Core block and permanent reflector stack axially [1]

3 HTTF Modeling using SAM

3.1 The SAM Computer Code

The System Analysis Module (SAM) is a modern system analysis tool being developed at Argonne National Laboratory for advanced non-LWR safety analysis. It aims to provide fast-running, whole-plant transient analysis capabilities with improved-fidelity for a wide range of advanced reactor types. SAM takes advantage of advances in physical modeling, numerical methods, and software engineering to enhance its user experience and usability. It utilizes an object-oriented application framework (MOOSE) [11], and its underlying meshing and finite-element library (libMesh) [12] and linear and non-linear solvers (PETSc) [13], to leverage the modern advanced software environments and numerical methods.

3.2 HTTF Model

The SAM input model for the HTTF is based on the ring model approach. In this approach, all components including the ceramic, heater, coolant channels, core barrel, pressure vessel, and RCCS are modeled as concentric cylindrical rings. A primary advantage of the ring model over the unit cell and block model approaches [5] is in its ability to model radial heat conduction which is the dominant heat transfer mode in Pressurized Conduction Cooldown (PCC) and Depressurized Conduction Cooldown (DCC) transient scenarios.

As previously described, the reactor is divided into several radial regions. Starting from the center, they are central reflector, inner core, middle core, outer core, side reflector, permanent reflector, core barrel, upcomer, and reactor vessel. There is a 2-mm stagnant helium gap on each side of the permanent reflector to accommodate ceramic expansion at elevated temperatures. The reactor is modeled using 47 rings shown in Figure 3.1. The 558 coolant channels are grouped into 11 coolant rings consisting of 1 ring in the central reflector; 3 each in the inner, middle, and outer heated core, and 1 in the side reflector. The permanent reflector is not actively cooled. The flow area (and thus ring thickness) is matched to the flow area of the coolant channels that are represented by the rings. The 210 heater rods are grouped into 9 heater rings with 3 rings each in the inner, middle, and outer core. A heater ring consists of a graphite heat structure and a 1-mm He gap on each side of the heat structure. Heat produced in the graphite heat structure is radiated to the ceramic via the He gaps. The ring thickness matches up with the heater hole cross sectional area. Each coolant ring and heater ring is sandwiched between two ceramic rings. The two surfaces of these two ceramic rings that form the walls of the coolant or heater ring are thermally equilibrated via surface coupling to prevent unphysical temperature discontinuity. There are total of 22 ceramic rings consisting of 2 rings in the central reflector, 6 in the inner core, 6 in the middle core, 5 in the outer core, 2 in the side reflector, and 1 for the permanent reflector. The ceramic ring thicknesses are determined based on the geometry of the core so that the radius of each radial region is properly captured in the geometric representation of the rings. The core barrel, upcomer and reactor vessel wall make up the final 3 rings in the reactor model. Outside the reactor vessel, two additional rings model the RCCS panels and water coolant. Table 3.1 presents a description of the 50 rings that make up the HTTF model and their dimensions.

Axially, the heated region is modeled with 10 elements corresponding to the 10 blocks. The upper and lower reflectors each have 2 axial elements. This axial meshing scheme applies to all

the radial regions in the reactor vessel. The coolant channels are modeled as 1-D fluid component. The ceramic and heater heat structure are modeled as 2-D components, with 5 elements in the radial direction. Above the upper reflector is the inlet plenum and below the lower reflector is the outlet plenum. Each plenum is modeled as one-dimensional volume branch. In normal operation coolant enters the reactor through an inlet pipe, flows up the upcomer into the upper plenum, downward through the upper reflector, the heated core region, the lower reflector and into the outlet plenum, then exits the reactor vessel through an outlet pipe.

Table 3.2.1 Description and geometry of rings in the HTTF ring model

Ring	Component	Description	SAM Type	Material	Inner radius	Thickness
1	Cent Refl	ceramic	PBCoupledHeatStr	GC-94F	0.0000	0.0903
2	Cent Refl	coolant	PBOneDFluidComp	He	0.0903	0.0030
3	Cent Refl	ceramic	PBCoupledHeatStr	GC-94F	0.0933	0.0874
4	Inner core	coolant	PBOneDFluidComp	He	0.1807	0.0058
5	Inner core	ceramic	PBCoupledHeatStr	GC-94F	0.1865	0.0120
-	Inner core	heater gap	SurfaceCoupling	He	0.1985	0.0010
6	Inner core	heater	PBCoupledHeatStr	graphite	0.1995	0.0052
-	Inner core	heater gap	SurfaceCoupling	He	0.2047	0.0010
7	Inner core	ceramic	PBCoupledHeatStr	GC-94F	0.2057	0.0120
8	Inner core	coolant	PBOneDFluidComp	He	0.2177	0.0051
9	Inner core	ceramic	PBCoupledHeatStr	GC-94F	0.2228	0.0120
-	Inner core	heater gap	SurfaceCoupling	He	0.2348	0.0010
10	Inner core	heater	PBCoupledHeatStr	graphite	0.2358	0.0041
-	Inner core	heater gap	SurfaceCoupling	He	0.2399	0.0010
11	Inner core	ceramic	PBCoupledHeatStr	GC-94F	0.2409	0.0120
12	Inner core	coolant	PBOneDFluidComp	He	0.2529	0.0052
13	Inner core	ceramic	PBCoupledHeatStr	GC-94F	0.2581	0.0120
-	Inner core	heater gap	SurfaceCoupling	He	0.2701	0.0010
14	Inner core	heater	PBCoupledHeatStr	graphite	0.2711	0.0033
-	Inner core	heater gap	SurfaceCoupling	He	0.2744	0.0010
15	Inner core	ceramic	PBCoupledHeatStr	GC-94F	0.2754	0.0115
16	Middle core	coolant	PBOneDFluidComp	He	0.2869	0.0046
17	Middle core	ceramic	PBCoupledHeatStr	GC-94F	0.2915	0.0085
-	Middle core	heater gap	SurfaceCoupling	He	0.3000	0.0008
18	Middle core	heater	PBCoupledHeatStr	graphite	0.3008	0.0048
-	Middle core	heater gap	SurfaceCoupling	He	0.3056	0.0008
19	Middle core	ceramic	PBCoupledHeatStr	GC-94F	0.3064	0.0085
20	Middle core	coolant	PBOneDFluidComp	He	0.3149	0.0048
21	Middle core	ceramic	PBCoupledHeatStr	GC-94F	0.3197	0.0085

-	Middle core	heater gap	SurfaceCoupling	He	0.3282	0.0008
22	Middle core	heater	PBCoupledHeatStr	graphite	0.3290	0.0042
-	Middle core	heater gap	SurfaceCoupling	He	0.3332	0.0008
23	Middle core	ceramic	PBCoupledHeatStr	GC-94F	0.3340	0.0085
24	Middle core	coolant	PBOneDFluidComp	He	0.3425	0.0049
25	Middle core	ceramic	PBCoupledHeatStr	GC-94F	0.3474	0.0085
-	Middle core	heater gap	SurfaceCoupling	He	0.3559	0.0008
26	Middle core	heater	PBCoupledHeatStr	graphite	0.3567	0.0038
-	Middle core	heater gap	SurfaceCoupling	He	0.3605	0.0008
27	Middle core	ceramic	PBCoupledHeatStr	GC-94F	0.3613	0.0077
28	Outer core	coolant	PBOneDFluidComp	He	0.3690	0.0044
29	Outer core	ceramic	PBCoupledHeatStr	GC-94F	0.3734	0.0130
-	Outer core	heater gap	SurfaceCoupling	He	0.3864	0.0010
30	Outer core	heater	PBCoupledHeatStr	graphite	0.3874	0.0042
-	Outer core	heater gap	SurfaceCoupling	He	0.3916	0.0010
31	Outer core	ceramic	PBCoupledHeatStr	GC-94F	0.3926	0.0130
32	Outer core	coolant	PBOneDFluidComp	He	0.4056	0.0043
33	Outer core	ceramic	PBCoupledHeatStr	GC-94F	0.4099	0.0130
-	Outer core	heater gap	SurfaceCoupling	He	0.4229	0.0010
34	Outer core	heater	PBCoupledHeatSr	graphite	0.4239	0.0026
-	Outer core	heater gap	SurfaceCoupling	He	0.4265	0.0010
35	Outer core	ceramic	PBCoupledHeatStr	GC-94F	0.4275	0.0130
36	Outer core	coolant	PBOneDFluidComp	He	0.4405	0.0040
37	Outer core	ceramic	PBCoupledHeatStr	GC-94F	0.4445	0.0130
-	Outer core	heater gap	SurfaceCoupling	He	0.4575	0.0010
38	Outer core	heater	PBCoupledHeatSr	graphite	0.4585	0.0033
-	Outer core	heater gap	SurfaceCoupling	He	0.4618	0.0010
39	Side refl	ceramic	PBCoupledHeatStr	GC-94F	0.4628	0.0900
40	Side refl	coolant	PBOneDFluidComp	He	0.5528	0.0020
41	Side refl	ceramic	PBCoupledHeatStr	GC-94F	0.5548	0.0880
42	Gap	gas	Surfacecoupling	He	0.6428	0.0084
43	Perm refl	ceramic	PBCoupledHeatStr	SiC-80	0.6512	0.0996
44	Gap	gas	Surfacecoupling	He	0.7509	0.0064
45	Core barrel	structure	PBCoupledHeatStr	SS	0.7572	0.0048
46	Upcomer	coolant	PBOneDFluidComp	He	0.7620	0.0572
47	Vessel	structure	PBCoupledHeatStr	SS	0.8192	0.0127
48	Gap	air	SurfaceCoupling	Air	0.8319	0.2000
49	RCCS wall	wall	PBCoupledHeatSr	ss-mat	1.0319	0.0020
50	RCCS panels	coolant	PBOneDFluidComp	H2O	1.0339	0.0100

Figure 3.2.1 Ring model of the HTTF core. The 1D flow channels, i.e., PBOneDFluidComponent, are marked green with their corresponding indices.

4 Steady State Results for Full Operating Power

As a first step, a steady state analysis was carried out to compare SAM simulation results with previous calculations using RELAP5-3D, and STAR-CCM+ [7]. Although HTTF has not operated at full power, the analyses assumed all heater blanks were operational with maximum power output of 2.2 MW and that axial heating profile was uniform. Material properties for Greencast GF-94 and silicon carbide were obtained from manufacturer's specifications [1]. Helium properties at 0.7 MPa were obtained from the NIST data base [14]. Air properties were available from the built-in equation of state in SAM. Inlet coolant flow rate was 0.965 kg/s with inlet temperature of 528 K. The flow rate was chosen so that temperature rise through the core matches with prototypical temperature in MHTGR. Bypass flow in the SAM simulation came to ~10.5% of total flow consisting of 8.2% in outer bypass channels and 2.3% in inner bypass. The bypass flow fraction is consistent with bypass flow in MHTGR [8]. Water coolant flowing in the RCCS panel was 1 kg/s with prescribed inlet temperature of 303.15 K. The RCCS in HTTF establishes the boundary conditions for the RPV.

Steady state results are presented in Table 4.1. Overall, there is good agreement between SAM results with results from RELAP5-3D and STAR-CCM+.

Table 4.1 Steady state results for 2.2 MW power

	SAM	RELAP5-3D	STAR-CCM+
Whole Core			
Mass flow rate (kg/s)	0.965	0.965	0.966
Inlet temperature (K)	528	528.8	528
Exit temperature (K)	962.7	960.2	959.8
Pressure drop (kPa)	3.1	1.7	NA
Heated core			
Mass flow rate (kg/s)	0.864	0.850	0.838
Exit temperature (K)	998.3	1003 - 1014.5	1007.5
Inner bypass (central reflector)			
Mass flow rate (kg/s)	0.022	0.017	0.027
Exit temperature (K)	675.0	728.4	665.9
Outer bypass (side reflector)			
Mass flow rate (kg/s)	0.079	0.099	0.100
Exit temperature (K)	655.0	630.4	640.6
RCCS			
Heat removal (MW)	0.024	0.05	Not modeled

5 Pressurized Conduction Cooldown Transient

In the MHTGR design, a Pressurized Conduction Cooldown (PCC) event is characterized the loss of forced flow but the pressure boundary of the reactor remains intact. The reactor scrams and the decay heat is transferred from the core 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. In the case of the HTTF, the RCCS forms a closed enclosure surrounding the vessel, so heat is transferred by thermal radiation from the vessel wall to the water-cooled RCCS panels.

An analysis was carried out to simulate a PCC transient in HTTF with 4 heater banks that deliver 700 kW heating power. In its current configuration only 4 of the 10 heater banks in the HTTF are operational. The heater locations are shown in Figure 5.1. Each heater bank consists of 3 legs and each leg has 7 heater rods. Table 5.1 shows the distribution of heater rods in the ring model for one 60-degree section. Note that the true location of rod 8 is in ring 26, but it is placed in ring 30 in the model, to avoid having disproportionately low power density if only one quarter of the heaters in ring 26 is active. It is also worth noting that this analysis is not intended to exactly simulate a PCC event in a MHTGR because of differences in the design, materials, and operating pressure between the HTTF and MHTGR. One such difference is that the graphite in the core and core reflectors in MHTGR conducts heat at significantly higher rate than the GF-94 ceramic in HTTF (the difference in thermal conductivity is more than an order of magnitude). The purpose of this analysis is to investigate the reactor cooldown behavior and heat transfer mechanism in HTTF without forced flow. Internal flow in the core exists only by natural circulation.

First steady state calculations were performed to establish the initial conditions. The PCC transient is then initiated at time = 0 in the simulations by tripping the gas blower which is assumed to coastdown linearly in 60 s. The input power, shown in Figure 5.2, decays according to typical MHTGR decay heat profile [9].

Figure 5.1 Location of 4 heater banks for PCC transient [OSU-HTTF-CORE-DWG-030-R1, provided by Dr. Brian Woods. Used with permission.]

Table 5.1 Active heater locations in 1/6 sector

Ring No.	No. of rods installed (1/6th sector)	No. of active rods	Heater #
6	3	0	-
10	3	0	-
14	3	3	10, 12, 14
18	4	3	9, 11, 13
22	4	0	-
26	4	0	-
30	5	4	2, 4, 6, 8
34	4	4	1, 3, 5, 7
38	5	0	-

Figure 5.2 Decay power profile, inserted figure shows expanded axis. The plot has been reconstructed using data from RELAP5-3D input file [6].

During normal operation, helium flows downward through the core coolant channels and its velocity is shown as negative by convention defined in this model. After forced flow is terminated, a natural circulation loop is established in the core and upward flow is indicated by positive velocity. **Figure 5.3** displays the helium velocity in various radial regions in the core during the PCC transient. In the central reflector (R2) and inner core (R4, 8, 12), shown in the top figure, as well as in the middle core (R16, 20, 24), shown in the middle figure, the flow reverses direction and flows upward. In the outer core region (R28, 32, 36), flow reverses direction initially but quickly returns to downward flow while the flow through the side reflector (R40) remains in downward direction throughout the transient. In summary, a closed natural circulation loop is established with downward flow in the outer region and upward flow in the inner region. A similar flow pattern has also been observed in a PCC transient simulation of the prototypical GA's MHTGR design [5]. It is worth noting that the velocity is two orders of magnitude lower than forced flow condition.

Figure 5.4 shows the temperature at three axial positions in ring 13 which is the third ceramic ring of the inner core (see **Table 3.2.1**). Block 1 is the bottom heated block, block 6 is just above midplane and block 10 denotes the top heated block. Similarly, **Figure 5.5** shows the temperature in ring 33 which is the first ceramic ring in the outer core. In normal operation the temperature of the ceramic increases axially from top to bottom as does the coolant. This can be seen in the figures at $t = 0$ where temperature increases from block 10 to block 1. Once forced flow is terminated, the ceramic temperature increases and peaks after about 2 days. Beyond that, heat loss from the reactor exceeds heater power output and so temperature in the ceramic begins to decline. Also, note that after about half a day, the axial temperature profile transitions to one that peaks in the middle (block 6) due to conduction to the unheated upper and lower reflectors. The small natural circulation velocity is not sufficient to maintain a monotonically increase or decrease in temperature along the axial direction. This is evidence that under natural circulation condition in the HTTF heat conduction dominates the heat transfer mechanism.

Figure 5.3 Helium velocity in the coolant channels in the central reflector and inner core (top), middle core (middle), and side reflector and outer core (bottom).

Figure 5.4 Temperature at three axial positions in Ring 13 in the inner core

Figure 5.5 Temperature at three axial positions in Ring 33 in the outer core

Figure 5.6 displays the axially averaged ceramic temperature in various radial regions. Going outward from the center, they are central reflector, inner core, middle core, outer core, side reflector, and permanent reflector. The axial average is the arithmetic average of the upper reflectors, the heated blocks and the lower reflectors. During normal operation, the temperature is higher in the heated core than in the reflectors. In the beginning of the PCC transient, all temperatures increase because of loss of coolant and peak after about 2 days and then decreases when heater power output is below the radiative heat loss from the reactor vessel wall to the RCCS. The central reflector becomes the hottest part in the later part of the transient as heat from the core is radially conducted toward the vessel wall.

Figure 5.7 shows the axially averaged temperature at the core barrel and reactor vessel wall. From the onset of the transient, input power drops significantly to simulate decay heat profile and as a result the temperature of the core barrel and reactor vessel decreases by about 40 degrees in the first 15 minutes. The temperature then increases and peaks after about 2 days before decreasing again through the remainder. At the peak, the core barrel and vessel reach 615 K and 530 K, respectively. **Figure 5.8** shows the RCCS water exit temperature. The trend is similar to the temperature of the reactor vessel. At its peak, the exit temperature is 2.5°C higher than its steady state temperature.

Figure 5.6 Axial average temperature in various radial ceramic regions

Figure 5.7 Axial average core barrel and reactor pressure vessel temperatures

Figure 5.8 RCCS water exit temperature. The inlet temperature is fixed at 303.15 K.

6 Depressurized Conduction Cooldown Test PG-26

Test PG-26 was the first major test conducted at the HTTF. The purpose of the test was to investigate the progression of the Double Ended Inlet-Outlet Crossover Duct Break transient. This test was referred to as the Depressurized Conduction Cooldown (DCC) test. It began on 5/30/2019 and ended on 06/03/2019. This test was operated with 2 heater banks (H104 and H110) which have total of 42 heater rods. The location of the heaters is shown in Figure 6.1. In the SAM model, the heaters are placed in ring 14 with 18 rods and ring 18 with 24 rods. Ring 14 is the outermost heater ring in the inner core region and ring 18 is the innermost heater ring in the middle core region. Each heater bank delivered peak power of more than 30 kW. The measured power profile, shown in Figure 6.2, is used as input in the simulation. The DCC was initiated in the 50th hour of the test when the valves positioned at both ends of the hot duct connecting the RPV and RCST were abruptly opened. Hot helium flowed from the RPV into the RCST in the top half of the duct while cold helium flowed from the RCST into the RPV in the bottom half [15]. Currently, SAM cannot properly simulate gas flow exchange progression between two volumes at different pressures, therefore the simulation is limited to the heat-up period prior to DCC. Helium inlet temperature, obtained from measured data in the upcomer (Figure 6.3) was used as input boundary conditions. There was no measurement for helium flow rate. In the simulation a guessed constant flow rate was used. It was later known that helium was leaking out of the RPV due to a valve failure, and cold helium from a bottle was added to the core which effectively reduced the core temperature. The amount of helium added was not specified. Because of the challenges encountered in this test, it is not meaningful to draw any conclusion in the comparison of SAM simulation with test data.

Figure 6.1 Heater location in Test PG-26 [OSU-HTTF-CORE-DWG-030-R1, provided by Dr. Brian Woods. Used with permission.]

Figure 6.2 Heating power measured in Test PG-26 [Used with permission].

Figure 6.3 Helium temperature in upcomer measured at lower reflector 3 position [Used with permission].

In light of the irregularity during this test, the focus this year is to map the hundreds of thermocouples in the facility [16] to approximate locations in the ring model so that test data can be compared with simulation results in future benchmarking of other HTTF tests.

Figure 6.4 compares the SAM results with test data for midplane ceramic temperatures at three radial regions: the central reflector, middle core, and side reflector. **Figure 6.5** shows the coolant temperature at midplane taken at the inner core, middle core and outer core. One notable trend observed in the data is the decrease in temperature from ~100000s to ~150000s. The decrease is most likely due to injection of cold helium to compensate for leaking helium through the failed valve. An examination of the test data also reveals an azimuthal dependence which is not the case in the model. The variation of temperature axially and azimuthally could have been affected by thermal movement between core blocks as the core heats up [17]. The movement could have misaligned the coolant channels between some of the blocks increasing flow resistance and reducing flow.

Figure 6.4 Comparison of SAM simulations in blue with test data in orange for axial midplane ceramic temperature taken at central reflector (top), middle core (middle), and side reflector (bottom)

Figure 6.5 Comparison of SAM simulations in blue with test data in orange for axial midplane coolant temperature taken at inner core (top), middle core (middle), and outer core (bottom)

7 Summary and Future Work

A ring model of the HTTF has been developed using SAM. The facility was modeled with 50 concentric cylindrical rings which cover all in-vessel components as well as ex-vessel RCCS. Steady state calculations for full power were performed and the results agreed well with those obtained from RELAP5-3D and STAR-CCM+. A PCC transient event was simulated to understand the thermal response behavior of HTTF when forced flow was cut off and core flow transitioned to natural circulation. The simulation revealed that natural circulation was not sufficient to maintain a monotonically increase or decrease temperature profile in the axial direction, and that radial heat conduction dominated the heat transfer mechanism in HTTF as is expected in MHTGR. Furthermore, it was recognized that although the ring model has an advantage over the unit cell and block model approaches in its ability to model radial conduction, there are limitations in accuracy particularly with respect to peak temperatures due to geometric simplification of a complex configuration of coolant channels, heaters, and structure. It is recommended to consider utilizing the 3D/1D coupling feature in SAM to provide more granularity in 3D-solid and 1D-fluid calculations to quantify uncertainty and/or improve accuracy in the ring model.

Benchmarking of the first major test – Test PG-26 – in HTTF was carried out. There were some unexpected challenges in the operation of the test and so it is not meaningful to compare SAM simulations with test data. Nevertheless, this initial benchmarking effort provides much insight as well as the needed setup for future benchmarking activities, particularly in mapping instrumentation locations to locations in the ring model. The HTTF test campaign has concluded with eight additional integral-level thermal fluid tests. It is recommended to further assess these tests and to perform code validation using these tests data.

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