Coupled Nuclear-Thermal-Hydraulics Analysis for VHTR

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1. INTRODUCTION

Effort has been made to determine the beginning-of-cycle (BOC) power distribution for the VHTR core at rated power of 600 MWt. The MCNP5 code [1] was coupled with the RELAP5-3D/ATHENA code [2] through a master process utilizing cross platforms to automate the process of performing coupled nuclear-thermal-hydraulic (NTH) calculations. We discuss the effect of thermal-hydraulic (TH) feedback on both homogeneous and heterogeneous core configurations.

2. COMPUTATIONAL METHODOLOGY

MCNP5 input decks were set up to represent the VHTR core with homogeneous and heterogeneous fuel assemblies, which are surrounded by reflectors and grouped into three annular rings, each ring comprising 10 axial fuel segments and clusters of 30, 36, and 36 fuel assemblies, respectively, for the inner, middle, and outer core rings. The heterogeneous configuration accounts explicitly for the double heterogeneities associated with the TRISO particles and fuel compacts, while the fuel and graphite in each assembly are uniformly mixed in the homogeneous representation. The pseudo material construct [3] was used to perform interpolations of cross section libraries generated at a few temperature points by the DOPPLER code [4]. This enabled us to avoid regenerating hundreds of new nuclear data libraries that exactly match the temperatures of the VHTR core being analyzed at each MCNP5-RELAP5 iteration.

Axial power fractions were determined for 10 axial zones for each of the three rings through MCNP5 calculations. Axial power fractions were input to RELAP5 to determine assembly-average temperature distributions. New RELAP5 temperature distributions were used for next MCNP simulation to obtain new power fractions. MCNP5 and RELAP5 iterations were performed in a cyclic fashion until convergence in temperature and power distributions were obtained. Furthermore, 100K particles per cycle were used with a total of 140 active cycles for each MCNP5 calculation.

The most CPU intensive part of the coupled NTH calculational system is MCNP5, which was compiled with MPI libraries using IBM XLF Fortran compiler to run on a powerful G5 cluster utilizing 8 CPUs in parallel. Furthermore, a cross platform architecture has been set up to couple MCNP5 and RELAP5 code systems, as illustrated in the overall flow chart of Figure 1. We illustrate in Table 1 how the data are communicated between MCNP5 and RELAP5-3D codes.

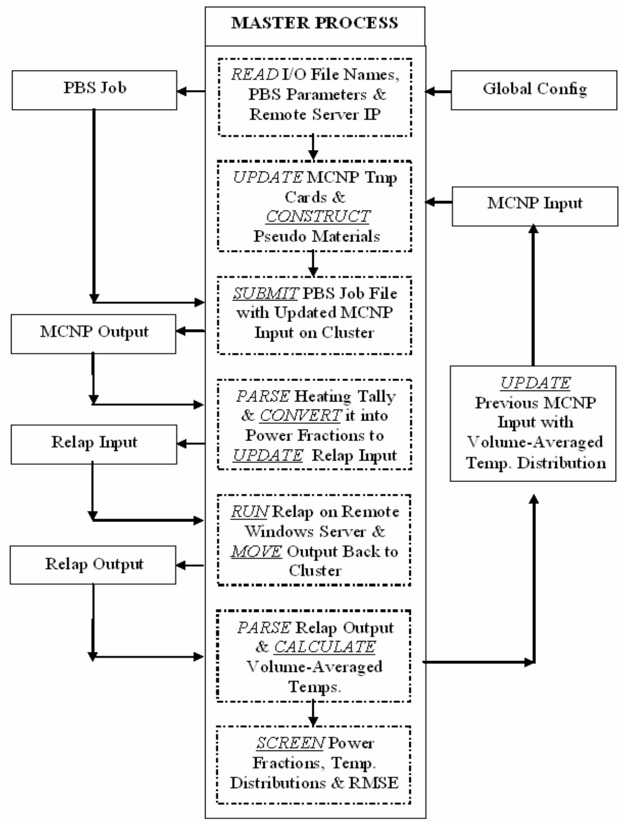

Figure 1. Architecture of coupled NTH system

3. RELAP5-3D ANALYSIS

For RELAP5-3D/ATHENA calculations, we modeled the core with three annular regions consisting of 30, 36, and 36 fuel stacks, consistent with the MCNP5 setup. Each annular region is axially discretized into ten segments and is represented [5] as a cylindrical coolant channel comprising a central coolant hole, surrounded by three inner graphite rings, four fuel rings, and one outer graphite ring. An adiabatic boundary condition is imposed at the outer boundary of the coolant channel. Based on the NGNP target [6] for the helium outlet

Table 1. Coupled NTH data communication for inner ring

	Power Frac. (MCNP5)	→ INPUT TO RELAP5	Temp. Dist. (RELAP5)	→ INPUT TO MCNP5	Power Frac. (MCNP5)	→ INPUT TO RELAP5	Temp. Dist. (RELAP5)
1	0.016574		926.045		0.028488		1038.256
2	0.026557		1050.207		0.041420		1205.862
3	0.035137		1175.686		0.047680		1333.691
4	0.041325		1293.021		0.047675		1419.931
5	0.045263		1401.488		0.043716		1475.861
6	0.045369		1486.089		0.038116		1513.388
7	0.041935		1543.885		0.031252		1531.816
8	0.035221		1570.742		0.023775		1533.103
9	0.025824		1564.520		0.016720		1523.647
10	0.015604		1533.804		0.010089		1503.648

temperature of 1273 K, together with the inlet temperature of 763 K, we determined a helium mass flow rate of 226 kg/s for rated power output of 600 MWt. A bypass flow fraction of 12.5 % was assumed, with the remaining flow distributed according to the number of fuel assemblies for each of the three coolant channels.

4. COUPLED NTH RESULTS

Converged temperature and power distributions for the inner, middle and outer rings are illustrated in Figure 2 for the homogeneous model, while a comparison is made in

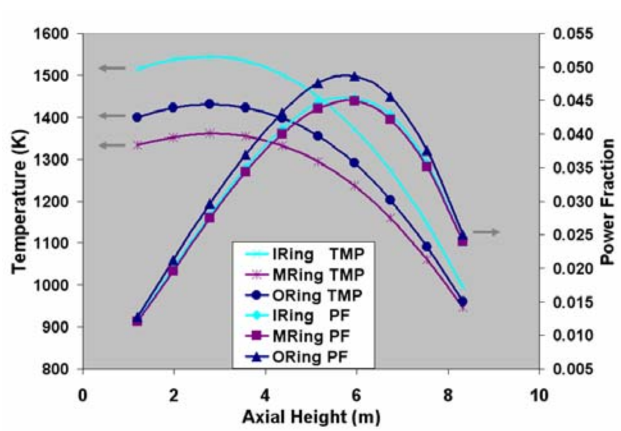

Figure 2. Converged power and temperature distributions for the homogeneous model

Figure 3 between the homogeneous and heterogeneous configurations. Figure 3 clearly indicates that the temperature distributions for the two representations are nearly identical, with differences of ~10 K. The power distributions for the homogeneous model were shifted a little more to the top of the core because of a more negative temperature coefficient of reactivity. The differences in the power distributions may be summarized by the axial offset (AO) of power, which is defined as the normalized difference in power between the top and bottom halves of the core. For the converged VHTR power distribution, we obtain AO of 16.2 % and 15.1 % for the homogeneous and heterogeneous core configurations, respectively.

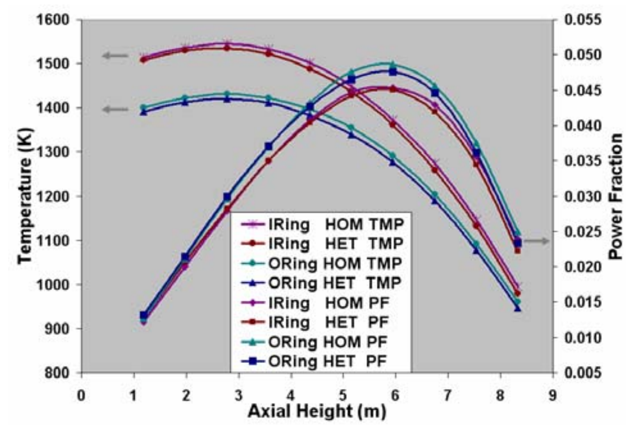

Figure 3. Comparison of Converged power and temperature distributions for the homogeneous and heterogeneous models

5. SUMMARY AND CONCLUSIONS

A cross-platform computer architecture connecting a Mac G5 cluster and a Windows server was successfully developed to automate the coupled NTH calculations for the VHTR core. Coupled MCNP5-RELAP5-3D calculations show that the converged power distributions are nearly independent of the heterogeneities represented in the neutronic calculations.

REFERENCES

1. Monte Carlo Team, 2003. MCNP – A General Monte Carlo N-Particle Transport Code, Version 5, LA-UR-03-1987. Los Alamos National Laboratory.
2. The RELAP5-3D Code Development Team, "ATHENA Code Manual," INEEL-EXT-98-00834, Rev. 2.2, Idaho National Engineering and Environmental Laboratory (2003).
3. Conlin, J.L., Ji, W., Lee, J.C., and Martin, W.R., "Pseudo Material Construct for Coupled Neutronic-Thermal-Hydraulic Analysis of VHTGR," *Trans. Am. Nucl. Soc. 92*, 225 (2005).
4. MacFarlane, R. E. and P. Talou, 2003, "DOPPLER: A Utility code for Preparing Customized Temperature-Dependent Data Libraries for the MCNP Monte Carlo Transport Code," Internal Memorandum, Los Alamos National Laboratory.
5. C. Davis, Private communication, June 2004.
6. P. E. MacDonald, "NGNP Preliminary Point Design – Results of the Initial Neutronics and Thermal-Hydraulic Assessments," INEEL/EXT-03-00870 Rev. 1, Idaho National Engineering and Environmental Laboratory (2003).