Impact of the Stochastic Distribution of Fuel Particles on VHTR Neutronic Analysis

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INTRODUCTION

Very High Temperature Gas-cooled Reactors (VHTRs) [1], both prismatic and pebble-bed designs, utilize TRISO fuel particles (with diameter 0.078cm) that are randomly distributed in fuel compacts or fuel pebbles. The stochastic distribution of TRISO fuel particles has an important effect on the neutronic analysis, including criticality eigenvalues and flux/power distributions.

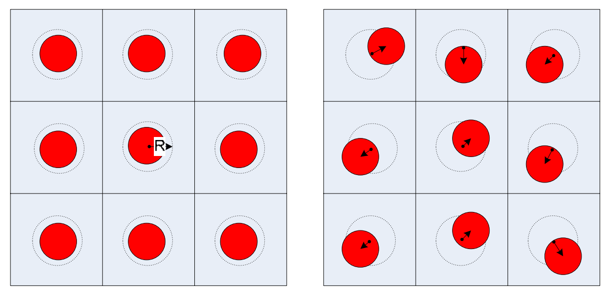
In this summary, several packing schemes which mimic the possible distributions of fuel particles in VHTR configurations are examined. These schemes include models based on assuming the fuel particles are arranged in a lattice structure, in a "jiggled" lattice structure, and a random structure based on the RSA (random sequential addition) method, which is a simple algorithm that places a sphere randomly in a container but rejects the placement if it overlaps another sphere or the container boundary. In each structure, two cases are investigated with different volume packing fractions (VPF): 28.92% and 5.76%, corresponding to prismatic type and pebble-bed reactors, respectively.

The probability density functions (PDFs) for the chord lengths between fuel particles are determined for each structure. The impact of the different particle distributions on the neutronic analysis is studied by calculating infinite medium Dancoff factors for the fuel particles. These results can also be used as benchmarks to validate the computational accuracy of analysis methods (such as chord length sampling [2,3,4]) used to analyze VHTR configurations.

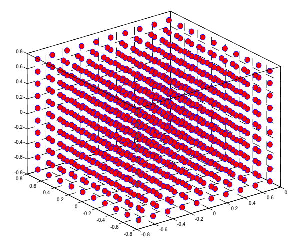
MODELING METHODS FOR FUEL PARTICLES IN GRAPHITE MATRIX

The study on random packing of hard spheres was originally performed when atomic arrangements were modeled in amorphous metals [5,6]. A similar problem is encountered in VHTR analysis because the fuel particles are hard spheres that are randomly distributed in the graphite matrix. Many packing methods have been proposed to model the arrangement of these fuel particles, including lattice and random structures [7,8,9,10]. However, none of these previous papers had been investigating the impacts of different packing methods on VHTR analysis.

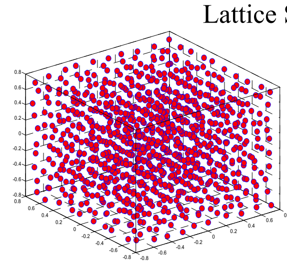
Figure 1 depicts the three fuel arrangements that are examined. The lattice structure is a simple cubic lattice with a microsphere fuel particle at the center of the cubic element which is sized to preserve the VPF of the fuel particles in the graphite matrix. About 20M fuel particles are modeled in the configuration. The jiggled lattice is created by randomly moving the center of each fuel particle within a bounding sphere of radius R, where R is typically a multiple of R_s, the radius of the fuel particle, and overlapping is not allowed. As R increases, the distribution of fuel particles will look more random and homogeneous. It is possible for a fuel particle to cross the boundary of a lattice cell if R is large enough.

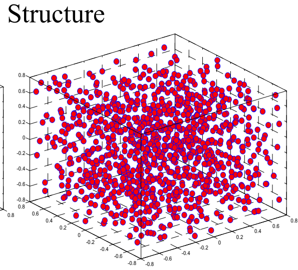


From Lattice to a Jiggled Lattice



Lattice Structure





Jiggled Lattice within 1.0*R_s RSA Structure

Figure 1. Different Packing Schemes.

Figure 1 illustrates the transition from a lattice structure to a jiggled lattice structure, as well as lattice, jiggled lattice, and RSA structures for a 3D realization. It is clear from Figure 1 that jiggling makes the distribution more isotropic and homogeneous than RSA, while the RSA model results in clumping of the fuel particles.

These effects will have important consequences for the neutronic analysis as will be discussed next.

RESULTS AND ANALYSIS

The geometry and composition of TRISO fuel particles are taken from a NGNP report [11]. The lattice, jiggled lattice, and RSA structures are constructed for the prismatic (28.92%) and pebble bed (5.76%) VPFs. For the random structures (jiggled lattice and RSA), the results are averaged over 100 realizations of the structures. Ray-tracing methods are used to calculate chord length distributions and Dancoff factors.

Chord Length Distribution between Fuel Particles

The PDFs for the chord lengths are determined in the following way: rays are emitted outwards with a cosine current distribution from the surface of a sphere and tracked to the first intersection with another sphere. This pathlength is tallied and a distribution of pathlengths is determined from these random samples. Figure 2 shows the chord length PDFs for the 28.92% and 5.76% VPFs. The relatively smooth behavior of the estimated PDFs for all chord lengths indicates that 100 realizations are sufficient.

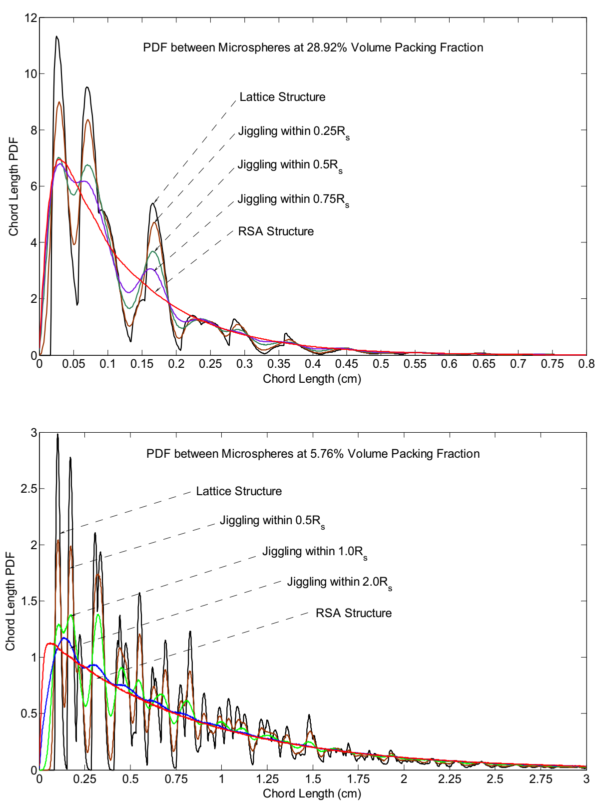


Figure 2. Chord Length PDFs for Two Different VPFs.

It is interesting that all the curves resemble a damped oscillator except the RSA model. The lattice model has the most oscillatory curve and the oscillations are damped as the amount of jiggling increases, converging to the RSA curve for large jiggling.

Another interesting phenomenon is that for large chord lengths, all the PDFs tend to follow the RSA curve. A previous paper [12] has shown that in the large chord length limit, the RSA distribution is exponential. Therefore, for large chord length, the chord length PDF is exponential regardless of the packing scheme, at least for the range of VPFs of interest to VHTR analysis.

Infinite Medium Dancoff Factors for Fuel Particles

The Dancoff factor for a fuel particle is defined as an average probability that a neutron escaping from a fuel kernel will enter another fuel kernel without any collisions with the intervening moderator region. The Dancoff factor is easily estimated with Monte Carlo simulation and was estimated for an infinite medium with different packing fractions. The results are shown in Table I.

Table I. Dancoff Factors at Different Packing Fractions

Different Packings		Dancoff Factors (1 σ)
5.76% VPF		
Lattice Structure		0.3299 (0.0001)
Jiggled Lattice within	0.5Rs	0.3324 (0.0001)
	1.0Rs	0.3363 (0.0001)
	2.0Rs	0.3375 (0.0001)
	3.0Rs	0.3386 (0.0001)
RSA Structure		0.3477 (0.0002)
28.92% VPF		
Lattice Structure		0.7314 (0.0001)
Jiggled Lattice within	.25Rs	0.7291 (0.0001)
	.33Rs	0.7284 (0.0001)
	.40Rs	0.7279 (0.0002)
	.50Rs	0.7275 (0.0001)
RSA Structure		0.7331 (0.0001)

The results show that the fuel particle arrangement has a significant effect on the neutronic analysis. For example, for 5.76% VPF, the Dancoff factor increases by 3% from a lattice to a highly jiggled lattice, but this is still 3% less than the RSA value. This is due to the increased clumping that arises for this low packing fraction for RSA or the highly jiggled lattices. This increases the self-shielding, or equivalently, the Dancoff factor. On the other hand, the opposite trend is observed for the 28.92% VPF case where the Dancoff factor decreases by about .5% with increasing jiggling in the lattice structure. Since this lattice is already tightly packed, the amount of jiggling was limited to .5Rs, which only results in local rearrangement of the particles rather than longer range clumping. Since the RSA lattice does allow for clumping, the Dancoff factor (and self-shielding) will be larger which is observed in Table I. Since the Dancoff factor has a strong effect on the resonance self-shielding, these changes will have a significant effect on k_{eff} for a VHTR configuration. This implies that the manufacturing process for packing the fuel particles into the fuel compact or fuel pebble has a strong effect on the neutronic analysis of the reactor. Modeling fuel particles in VHTR using a realistic packing scheme that represents the manufacturing process would yield more accurate neutronic analyses. This is consistent with the conclusions of Murata et al [7], who was the first researcher to incorporate knowledge of the actual fabrication process into the modeling of fuel particles for the VHTR.

CONCLUSIONS

When analyzing fuel particles in VHTR, different packing schemes yield different statistical properties which may be characterized in terms of chord length distribution functions. These in turn have a strong impact on the neutronic analysis, specifically the Dancoff factor and resonance self-shielding. This suggests that accounting for the manufacture process in the modeling of fuel particle arrangement in VHTR would improve the accuracy of the neutronic analysis of VHTR configurations. As a further verification, direct criticality (k_{eff}) calculations will be performed at different packing schemes in the future work.

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REFERENCES

1. A Technology Roadmap for Generation IV Nuclear Energy Systems, GIF-002-00, Generation IV International Form, (Dec. 2002). http://www.ne.doe.gov/genIV/documents/gen_iv_roadmap.pdf.
2. T. J. DONOVAN, Y. DANON, "Application of Monte Carlo Chord-Length Sampling Algorithms to Transport through a Two-Dimensional Binary Stochastic Mixture," *Nucl. Sci. Eng.,* **143**, pp.226-239 (2003).
3. W. JI, W. R. MARTIN, "Monte Carlo Simulation of VHTR Particle Fuel with Chord Length Sampling," M&C + SNA 2007, Monterey, California, April 15-19, 2007.
4. W. JI and W.R. MARTIN, "Application of chord length sampling to VHTR unit cell analysis," Proceedings of PHSOR08, Interlaken, Switzerland, September 14-19, 2008.
5. G. S. CARGILL, "Dense Random Packing of Hard Spheres as a Structural Model for Noncrystalline Metallic Solids," *J. Appl. Phys.*, **41**, 2248 (1970).
6. C. H. BENNETT, "Serially Deposited Amorphous Aggregates of Hard Spheres," *J. Appl. Phys.,* **43**, 2727 (1972).
7. I. MURATA, ET AL., "Continuous Energy Monte Carlo Calculations of Randomly Distributed Spherical Fuels in High-Temperature Gas-Cooled Reactors based on a Statistical Geometry Model," *Nucl. Sci. Eng.* **123**, 96-106 (1996).
8. R. PLUKIENE, D. RIDIKAS, "Modeling of HTRs with Monte Carlo: from a homogeneous to an exact heterogeneous core with microparticles," *Annals of Nuclear Energy,* **30**, 1573 (2003).
9. F. B. BROWN, W. R. MARTIN, "Stochastic Geometry Capability in MCNP5 for the Analysis of Particle Fuel", *Annals of Nuclear Energy*, **31**, 2039 (2004).
10. W. JI, J. L. CONLIN, W. R. MARTIN, J. C. LEE, F. B. BROWN, "Explicit Modeling of Particle Fuel for the Very-High Temperature Gas-Cooled Reactor," *Trans. Am. Nucl. Soc.*, **92**, 236 (2005).
11. P. E. MACDONALD, ET AL., "NGNP Preliminary Point Design-Results of the Initial Neutronics and Thermal-Hydraulic Assessments During FY-03," INEEL/EXT-03-00870 Rev. 1. Idaho National Engineering and Environmental Laboratory (2003).
12. W. JI, W. R. MARTIN, "Determination of Chord Length Distributions in Stochastic Media Composed of Dispersed Microspheres," *Trans. Am. Nucl. Soc.,* **96**, (2007).