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Pebble bed reactor modeling using Serpent

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Content

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Introduction

Introduction

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- Lappeenranta University of Technology is focusing on the modeling of pebble bed reactors as a part of NETNUC (New Type Nuclear Reactors) project funded by the Academy of Finland.
- Modeling tools are developed and tested to model the reactor physics, thermal-hydraulics and behavior of fuel pebbles.
- Serpent is currently used in the reactor physics modeling.

Pebble bed reactor (PBR)

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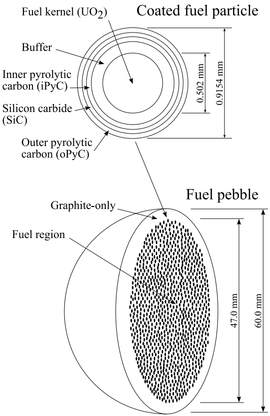

Figure: Schematics of a coated fuel particle and a cut-in-half fuel pebble.

Figure: Pebbles inside an annular core cavity.

Available models in Serpent

Particle fuel models in Serpent

- There are basically three ways to model particle fuel in Serpent.
  1. A regular lattice of particles inside a pebble.
  2. An implicit approach where particles are sampled during the random walk.
  3. All particles are given position coordinates in a separate input file.

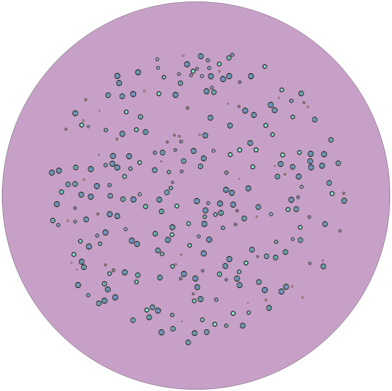

Figure: Coated fuel particles explicitly defined inside a pebble.

Pebbles in the core

- The pebbles could be put in a regular lattice, which is the usual approach in MC simulations.
- In Serpent, the positions of pebbles can be given in a separate input file the same way as coated particles.
- Defining the pebbles in a dense random configuration requires some effort.
- Discrete Element Method (DEM) can be used to create a very realistic pebble bed.

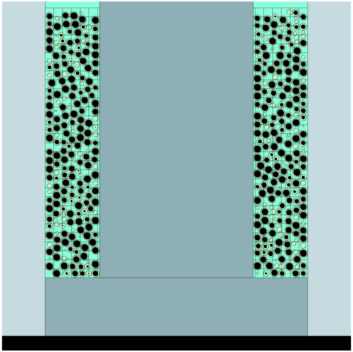

Figure: Stochastic configuration of pebbles inside an annular cavity.

Advantages of Serpent in pebble bed calculations

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- HTGR specific geometry types and methods allow easy modeling.
- Delta-tracking provides speedup in geometries with lots of details.
- Packed beds created with DEM can be used directly.

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ASTRA criticality calculations

ASTRA critical experiments

- Five ASTRA critical pebble bed experiments that were done at the Kurchatov Institute during 2003-2004 and documented in the IRPhEP Handbook are calculated.
- A cylindrical steel vessel where graphite blocks were assembled to form an octagonal annular cavity for the fuel spheres.

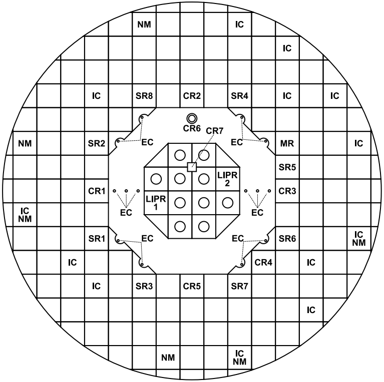

Figure: ASTRA annular core setup.

Building the model

- A very detailed geometry model is built based on the available data in the benchmark documentation.
- DEM is used to pour the pebbles inside the cavity.
- Serpent reads in the pebble position coordinates.
- Coated fuel particles are modeled in detail and explicitly defined inside the pebbles.

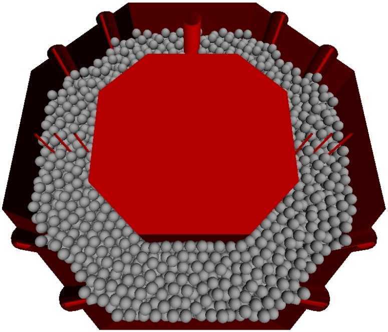

Figure: Pebbles inside the ASTRA cavity.

Serpent Geometry

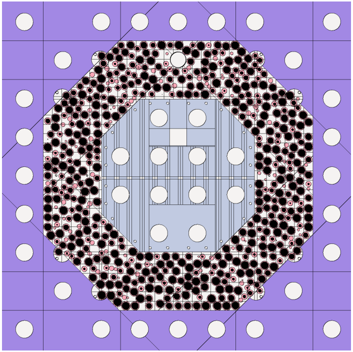

Figure: Horizontal cut of the ASTRA geometry model.

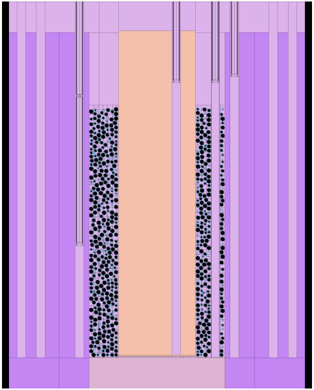

Figure: Vertical cut of the ASTRA geometry model.

Criticality calculation results

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- Calculations result in approximately 1000 pcm overestimation.
- Performed sensitivity analyses don't reveal the cause.
- Similar overestimation has been witnessed by others e.g. with MCNP.
- Testing of different cross-section libraries is anticipated in the future, especially JENDL-4.
- One case took 16 hours with five Intel Core i7 processors and 36 parallel tasks in total.

Table: Multiplication factors calculated by Serpent.

Core	$k_{\mathrm{eff}} \pm 1\sigma$ (experiment)	$k_{\mathrm{eff}} \pm 1\sigma$ (simulation)
1	1.0000 $\pm$ 0.0036	1.01052 $\pm$ 0.00008
2	1.0000 $\pm$ 0.0036	1.01040 $\pm$ 0.00008
3	1.0000 $\pm$ 0.0036	1.01086 $\pm$ 0.00008
4	1.0000 $\pm$ 0.0036	1.01005 $\pm$ 0.00008
5	1.0000 $\pm$ 0.0036	1.01096 $\pm$ 0.00008

Table: Results of the sensitivity analysis of core one.

Changed parameter	$k_{\mathrm{eff}} \pm 1\sigma$
Core height 182.30 cm	1.00950 $\pm$ 0.00008
JEFF-3.1	1.01084 $\pm$ 0.00008
ENDF/B-VII	1.01112 $\pm$ 0.00008
Graphite impurities 1.1 ppm boron	1.00777 $\pm$ 0.00008

Thermal-hydraulics coupling

Thermal-hydraulics (T-H) coupling

- Aim is in steady state full-core PBR calculations.
- Due to helium coolant, there are no phase changes...
- ...but the exceptional geometry sets new challenges.
- For T-H, the general-purpose CFD-code ANSYS Fluent is used.
- A coupling code connecting Serpent and Fluent is written in Perl.

Reactor physics model

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- Geometry is modeled like in the ASTRA case.
- Temperatures are changed by the internal Doppler broadening routine of Serpent.
- Serpent writes the pebble-wise power data as the result.

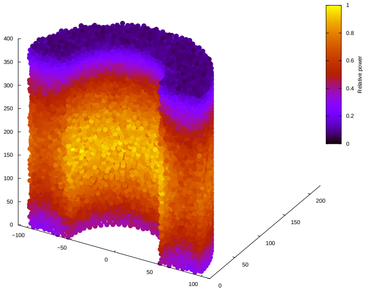

Figure: Half of a pebble bed showing the power distribution.

Thermal-hydraulics model

- Solving the flow and heat transfer in detail with CFD is not possible at the moment or in the near future.
- Porous medium approach is used so that the pebble bed is divided into bigger cells where parameters are averaged.
- Temperatures in calculation cells are written as the result.

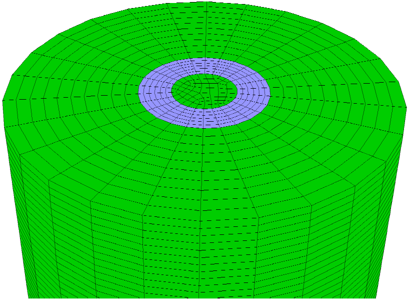

Figure: Calculation mesh of the T-H model.

Coupling code

- A coupling code is written in PERL.
  - Creates input files.
  - Controls the calculation processes.
  - Determines convergence.

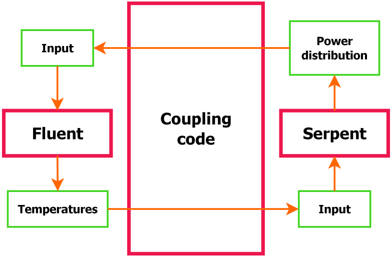

Figure: Coupled calculation scheme

Remaining obstacles and development areas

- Memory requirements of the material data and the calculation power demand.
- Fundamental differences between the codes (discrete vs. continuum).
- T-H model needs more work.
  - Mapping the packing structure accurately to the T-H model cells.
  - Developing the heat transfer model.
- Finalizing the coupling code.

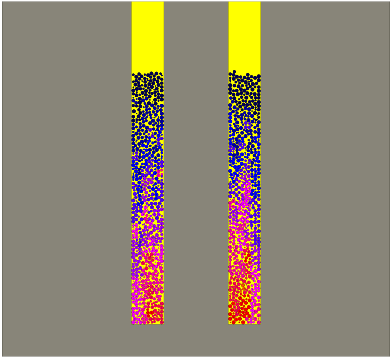

Figure: Serpent model showing different temperature regions after a T-H iteration

Test case

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- A test case with 50,000 pebbles, 30 different temperatures for the pebbles and $30 \cdot 10^6$ neutron histories was calculated.
- Calculations were done with an Intel Xeon E5520, 2.27GHz, 12 GB utilizing 4 parallel MPI tasks.
- Five iteration cycles took about 30 hours.

Conclusions

Conclusions

- Serpent is more than well equipped for PBR calculations.
- Complicated geometries can be built and the double-heterogeneous fuel modeled in full detail.
- Serpent is relatively fast in PBR calculations.
- Coupling of Serpent with T-H in for PBR calculations can be done with moderate effort.

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Thank you for your attention!