Engineering Expo Presentation

Multiphysics Modeling of a Pebble Bed Reactor

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1: **Background** (Slides 3-7)
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Background
Reactor Generations

- Reactor designs are split into generations
- The majority of reactors in America are generation II and III
- The industry is currently working towards Generation IV
- Gen. IV has many advantages:
  - Cost Effective
  - Inherent and Enhanced safety
  - Proliferation Resistant
- Pebble-Bed Modular Reactor (PBMR)

**Generation IV:** Nuclear Energy Systems Deployable no later than 2030 and offering significant advances in sustainability, safety and reliability, and economics

**Background**

[NERAC, GIF, 2002]
Background

TRISO Fuel

- TRISO (TRI-structural ISOtropic) fuel starts with enriched uranium (UO$_2$) reactor fuel kernel
  - Fuel kernels are covered in multiple layers of graphite and ceramics
- The final product is a fuel sphere, these spheres have many advantages over rod forms of reactor fuel:
  - High temperature resistance, Contains the fission products, Structurally sound, and Nearly impossible to extract the uranium

[NEA, 2013]
Background

Pebble Bed

- Pebble bed reactors use TRISO fuel spheres within the reactor core
- The uranium inside these fuel spheres causes a reaction which produces heat
- Helium gas is pushed through the gaps in between the pebbles to remove heat

[Cogliati, 2006]
Pebble Bed Reactor

- The reactor for this project is a pebble-bed reactor
- Fuel pebbles are contained within the annular region of the reactor core
- Annular means ring shaped cylinder
- We have restricted our model to just the area outlined in blue

[NEA, 2013]
Significance

Oregon State University
Significance

Comparison Between Two Methods

• This project compares two reactor core modeling methods
• The assumptions made in each model affect the neutron physics (neutronics)
• The first model is of a homogeneous core
  – Physically unrealistic but proven and provides acceptable results
• The second is a core using a Pebble-Tracking Transport (PTT) algorithm
  – Physically realistic but unproven and computationally expensive
Pebble Packing Factor

- Packing fraction is the amount of space occupied by the pebbles within a certain volume.
- Important to understand fluctuations throughout the core so we can determine its impact on the reactor performance.

Packing Fraction = \frac{\text{Volume of pebbles}}{\text{Volume containing pebbles}}
Homogeneous Model

- Assumes a single homogenized material for the core; a mixture of all the pebble materials into one “blob”

Significance

E.g.

[Cogliati, 2006]
**Significance**

**Pebble Tracking Transport Model**

- Tracks each pebble individually, this is much more realistic
- More precision in neutronics modeling for the core over the homogenized method

Individual pebbles within the core region modeled as nodes
Accident Scenarios to Compare Methods

- Two accident scenarios will be used in the comparison between modeling methods
- Accident scenarios for this project:
  - Before and after a seismic event (earthquake)
  - Depressurized Loss of Forced Coolant (DLOFC)
- These scenarios represent design-basis accidents individually and beyond design-basis accidents when coupled
  - Important for risk assessment and safety analysis for regulators like the Nuclear Regulatory Commission (NRC)
Significance

Accident Scenario: Seismic Event

- This accident scenario will simulate an earthquake
- The event will shake the core and force the pebbles to become more densely packed and therefore a higher packing fraction
- As the fuel is more densely packed, the reactivity of the core will increase which leads to increased power and temperatures

[Chen et al., 2020]
Significance

Accident Scenario:
Depressurized Loss of Forced Coolant (DLOFC)

- Depressurized Loss of Forced Coolant (DLOFC)
- In this scenario we simulate the aftermath of an accident where the reactor loses its coolant, i.e., coolant is no longer flowing through the core.
- Core materials including the fuel will begin to heat up significantly.
- Optimal upper limit for fuel is 1600°C.

[Strydom et al., 2010]
Significance

MAMMOTH

• For regulators it is important to have a comprehensive code that can represent both normal operation and an accident scenario, and MAMMOTH is promising.
• MOOSE is the INL Multi-Physics Framework that allows for the construction and solving of Partial Differential Equations (PDEs) that represent physical system behavior.
• MAMMOTH is a MOOSE Module specifically designed for simulating Reactors.
• Capable of simulating both a reactor in steady state and with transients (constant conditions vs. changing).
• A goal of this project is to evaluate the performance of MAMMOTH for PBRs.
• MAMMOTH takes an input file that includes the mesh of our core and a set of properties which we define to the core regions.
CUBIT/TETGEN

- Meshing softwares used for homogenized and the PTT base model respectively.
- CUBIT utilizes an Add-On developed by INL specifically for this style of core that optimizes the mesh for neutronics of reactors.
- TetGen is used to handle the large amount of elements for the PTT meshes, can even model individual elements.
- Both are methods that are commonly used by the industry and research professionals.

Individual pebbles within the core region
PEBBLES

Significance

• Developed by Dr. Cogliati at INL, DEM code specifically for modeling pebble distribution.
• All fuel spheres are treated as individual elements, with their own center location and a set physical properties.
• At a starting point the real life forces acting on a pebble are converted to equations the code can interpret.
• At subsequent time steps, resultant equations from the system and collisions of elements.
What Will These Models Show?

- Each accident scenario model will show neutronics or heat conduction results.
- On the right is a MAMMOTH output for a pre-seismic Homogenized Diffusion.
- Left part of the image represents thermal flux, right side power density.
Design Challenges
Design Challenges
Preparing Input Files

- List of 450,000 pebble center coordinates
- Need to visualize packing fraction distribution throughout the core
Design Challenges
Making Simplifications

• We are not going to be able to model the core perfectly.

• The key is knowing what assumptions you can reasonably make.
Design Challenges

Running the Simulation

- Important to know what your code (MAMMOTH) is actually doing
- Know what to modify between our three scenarios
- How do we implement packing factor?

Pebble-bed effective thermal conductivity:

\[
(1 - \epsilon)\rho_s C_{p,s} \frac{dT_s}{dt} - \nabla \cdot (\kappa_s \nabla T_s) + \alpha (T_s - T_f) + \dot{q}_s = 0
\]

Porosity (Related to packing factor)

Temperature of Solid (What we are solving for)

Neutron Diffusion Equation:

\[
\frac{1}{v} \frac{\partial \varphi}{\partial t} = s - \Sigma_a \varphi + D \nabla^2 \varphi
\]
Questions?

Oregon State University
References 1/2


References 2/2


