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Power profile assessment for coupled thermal hydraulic and neutronic calculation for HTGR application



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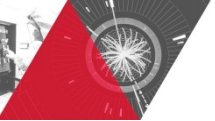
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New reactor concepts and safety analyses for the Polish Nuclear Energy Program

POWR.03.02.00-00.I005/17

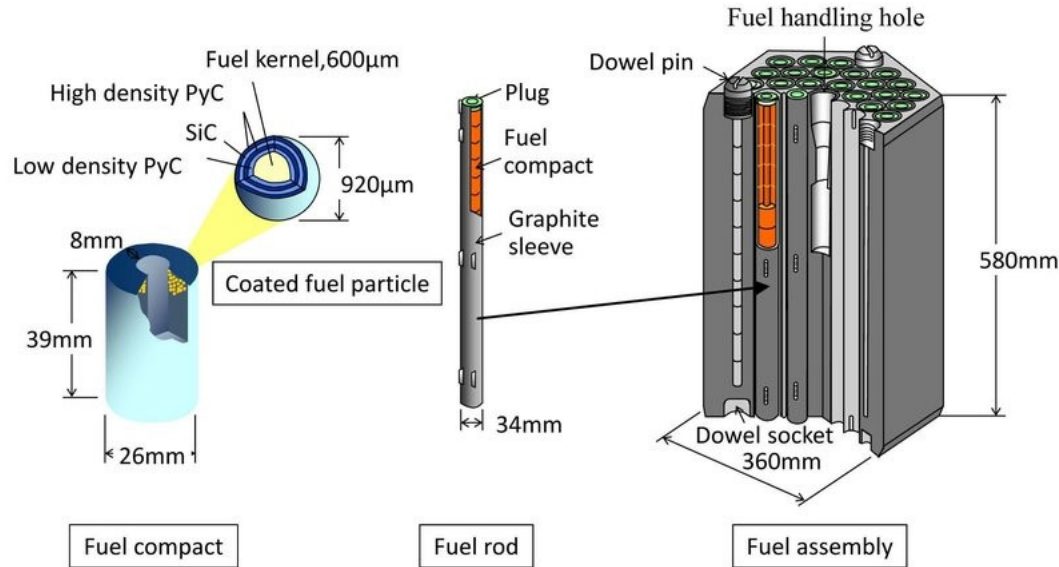


- Introduction
- Motivation
- Current work – OpenFoam
- Current work - Serpent
- Power distribution assessment
- Coupling MCB+POKE+OpenFoam
- Conclusions



- PhD topic:
Development of coupled neutronic and CFD calculations for HTGR applications
- Supervisor
prof. dr hab. inż. Jerzy Cetnar
- Auxiliary supervisor
dr inż. Jakub Sierchuła
- HTGR
 - Reactor concept
 - High Temperature Gas-cooled Reactor
 - Helium as coolant
 - Graphite as moderator
 - Fuel in TRISO particles
- HTTR
 - Existing reactor
 - High Temperature engineering Test Reactor
 - The Oarai Research and Development Center, Japan
 - Thermal power 30 MW
 - Maximum outlet temperature 950 °C

- TRISO particles are incorporated into fuel compacts with a graphite matrix
- The fuel rod is contained within a vertical hole of a graphite block.



Configuration of the HTTR fuel element.

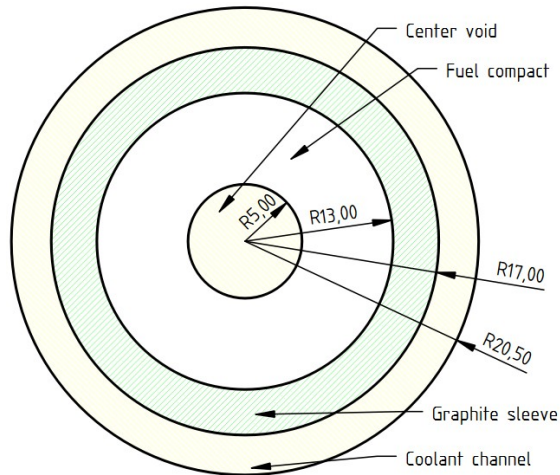
Source: A SMALL MODULAR REACTOR DESIGN FOR MULTIPLE ENERGY APPLICATIONS: HTR50S, Nuclear Engineering and Technology, Volume 45, Pages 401-414, 2013
M.Górkiewicz, Power profile assesment for coupling on HTGR



Motivation – Neutronic properties of HTGRs

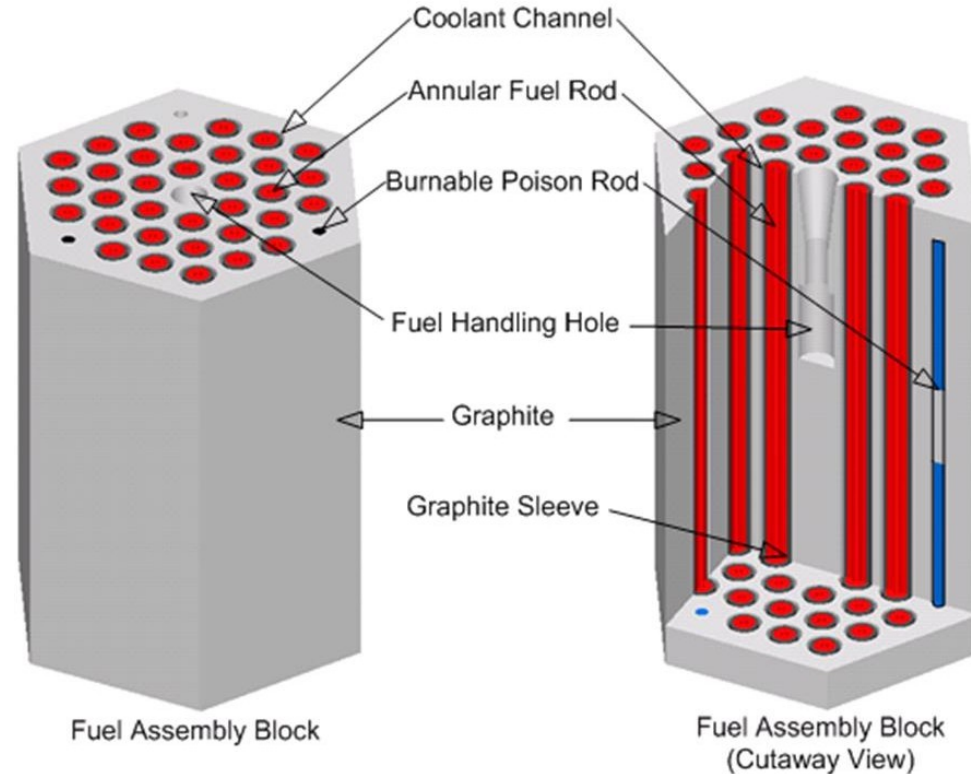
- Deep neutron thermalisation
- Large migration length
- Local neutron spectrum is strongly influenced by:
 - Control rods
 - Burnable poisons
 - Reflectors
- High neutron flux gradients
- Power peaks
- Double heterogeneity
 - Caused by fine structure of compacts filled with TRISO particles
 - Highly structured geometrical model is needed to account for neutron spectra effects that occur in the fuel due to resonant cross sections
- Neutronic cross section dependence on temperature
- Coolant is neutron transparent

- In order to get temperature profile in fuel and moderator, single fuel rod was modelled using open source CFD software - OpenFoam



HTTR fuel rod structure.

Source:[4]



Fuel Assembly Block

Fuel Assembly Block
(Cutaway View)

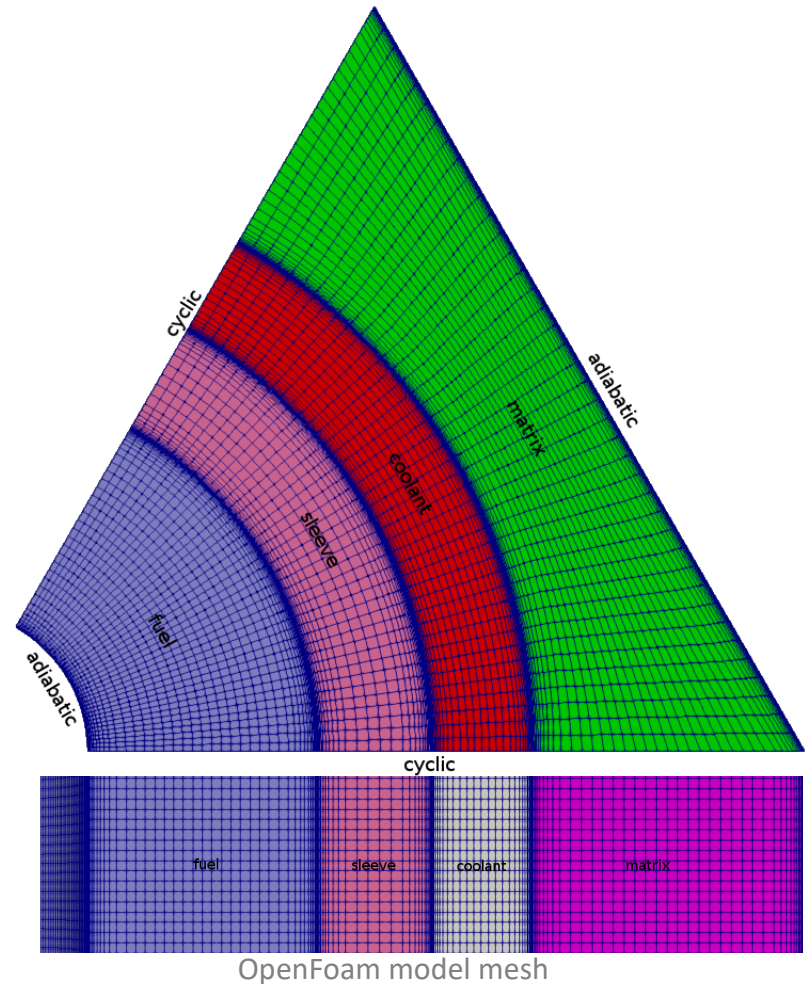
HTTR prismatic fuel block.

Source: Ames, David E..Nuclear fuel cycle system simulation tool based on high-fidelity component modeling., 2014

Current work - OpenFoam

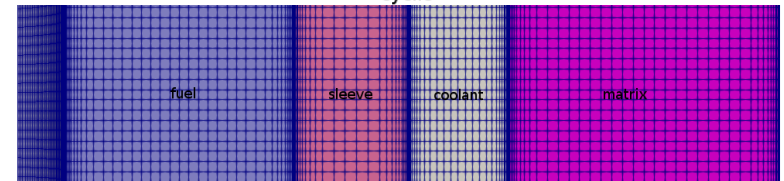
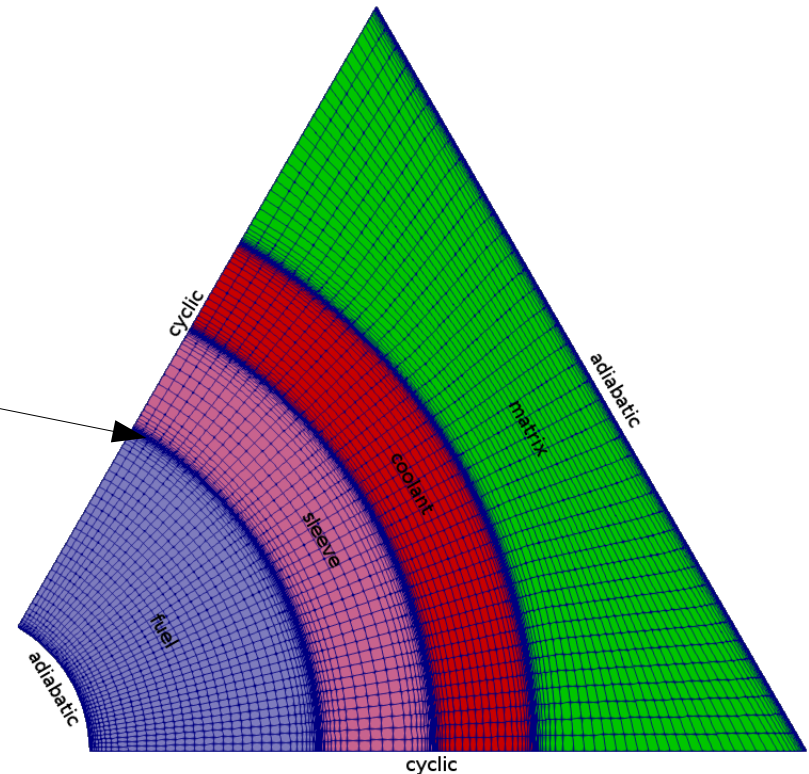
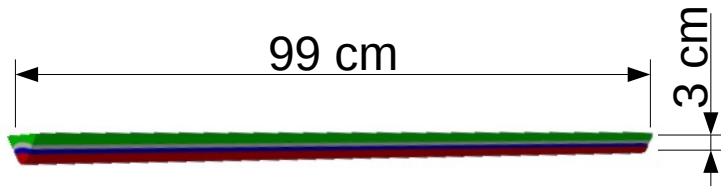
The chtMultiRegionFoam solver is used to simulate heat transfer from fuel to coolant and graphite structures in a fuel block

- Reflective boundary conditions set to make the case infinite horizontally.
- Geometry divided into 4 regions
- Heat generation applied in the fuel region.
- Adiabatic boundary condition at inner wall – assumption of thermal equilibrium due to lack of flow in closed space.
- Coolant as fluid region, k- ω SST turbulence model applied. Heat transfer by convection.



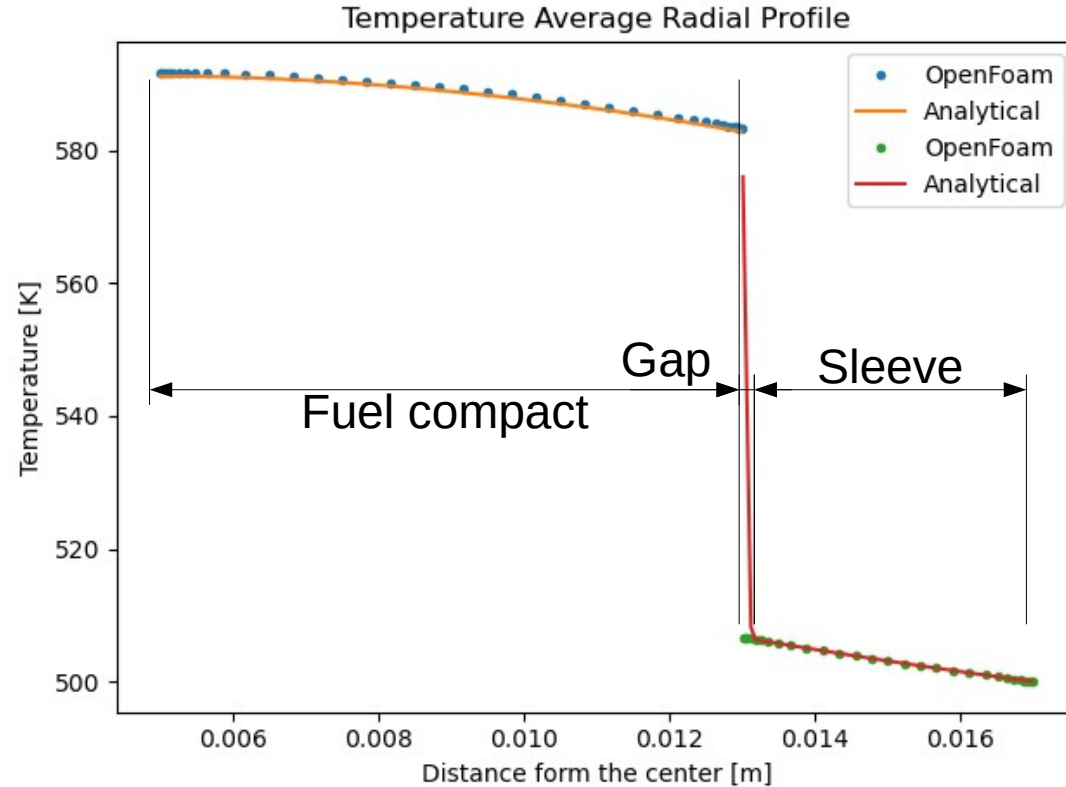
Current work - OpenFoam

- Mesh size in the fuel region adjusted to size of a TRISO particle – the largest mesh cell is small enough to be inscribed in the TRISO particle.
- Helium gap between fuel and sleeve.
- Mesh size in the coolant set to $y^+ = 1$
- Fixed temperature, pressure and flow rate at inlet
- Material properties dependence on temperature



OpenFoam model mesh

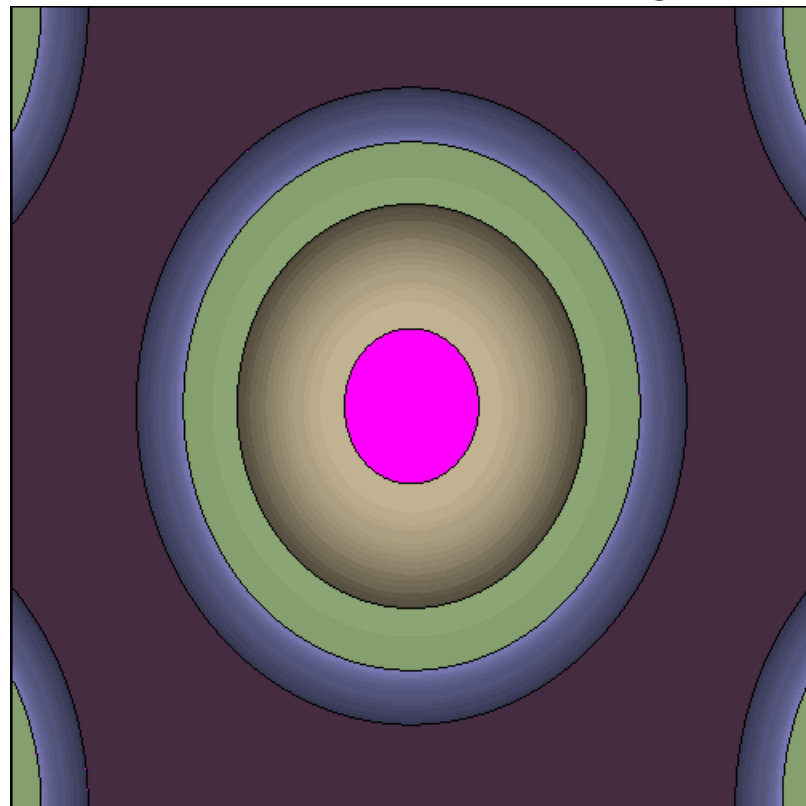
- Introduced helium gap between fuel pellet and sleeve as a thin thermal resistance layer within a boundary condition.
- In order to validate it, simplified cylindrical geometry was created and results were compared to analytical solution of the Poisson and Laplace equations.



flow and constant properties.

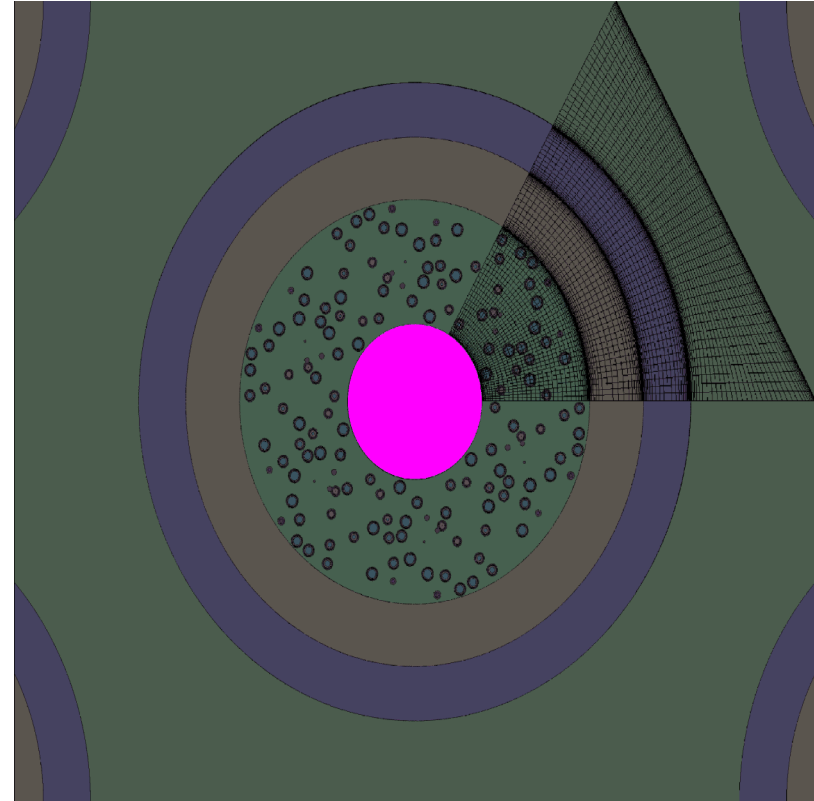


- The multi-physics interface is a set of routines, as well as input/output formats intended for easily bringing in detailed temperature and density fields to Serpent and at the same time automatically producing power distributions to be used in coupled codes. [6]
- Serpent case was created and linked to the OpenFoam case.
- Temperature field from OpenFoam is imported with resolution of the case mesh.



Serpent case for HTTR homogenized fuel compact
with imported temperature distribution from
OpenFoam.

- Detail mesh including TRISO particles in OpenFoam is a tremendous task – fuel have to be homogenized for CFD simulation.
- Serpent produces power distribution with precision of a mesh cell – not every cell contain TRISO particle. However, cell-wise power profile can be further exported to the OpenFoam.
- For technical reasons, Serpent case cannot be reduced to 1/6th of fuel rod like the OpenFoam case. This issue was solved with help of the Serpent developers by introducing temperature symmetry in the source code.



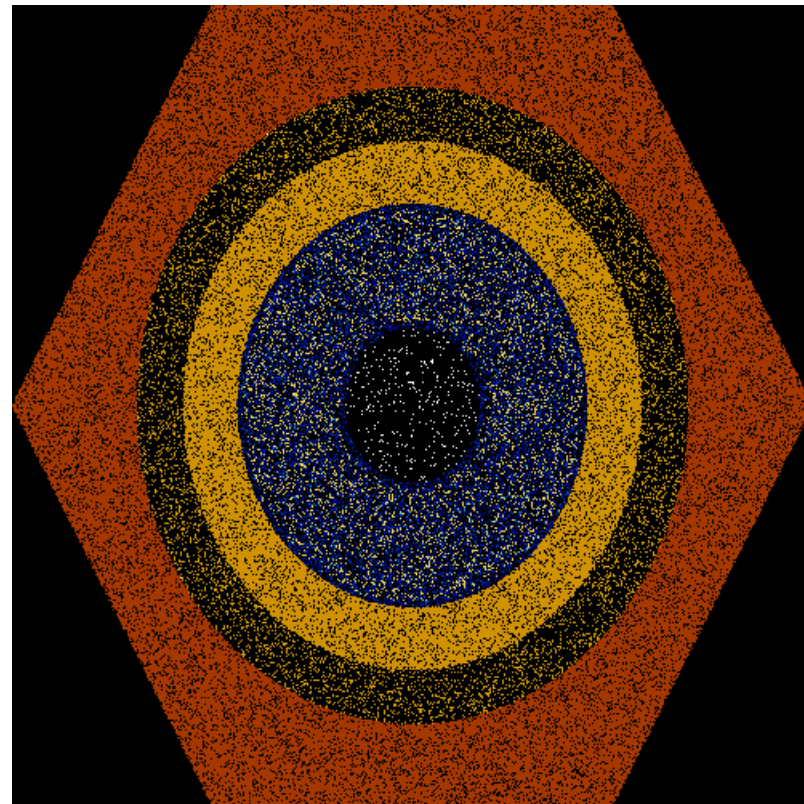
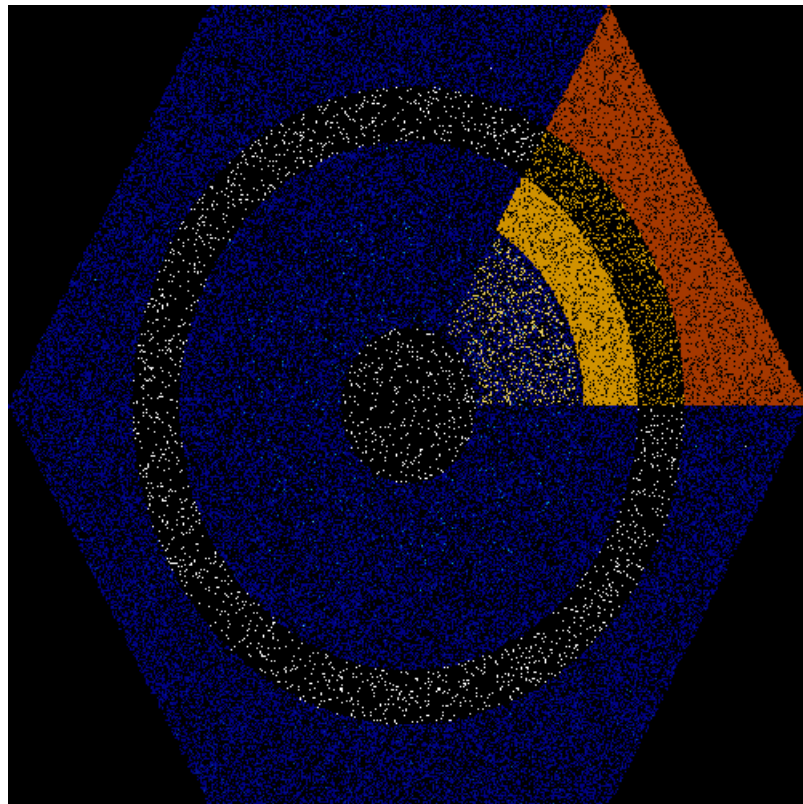
Serpent case for HTTR fuel compact and related
OpenFoam mesh



Challenges in coupling Serpent and OpenFoam

Before modification

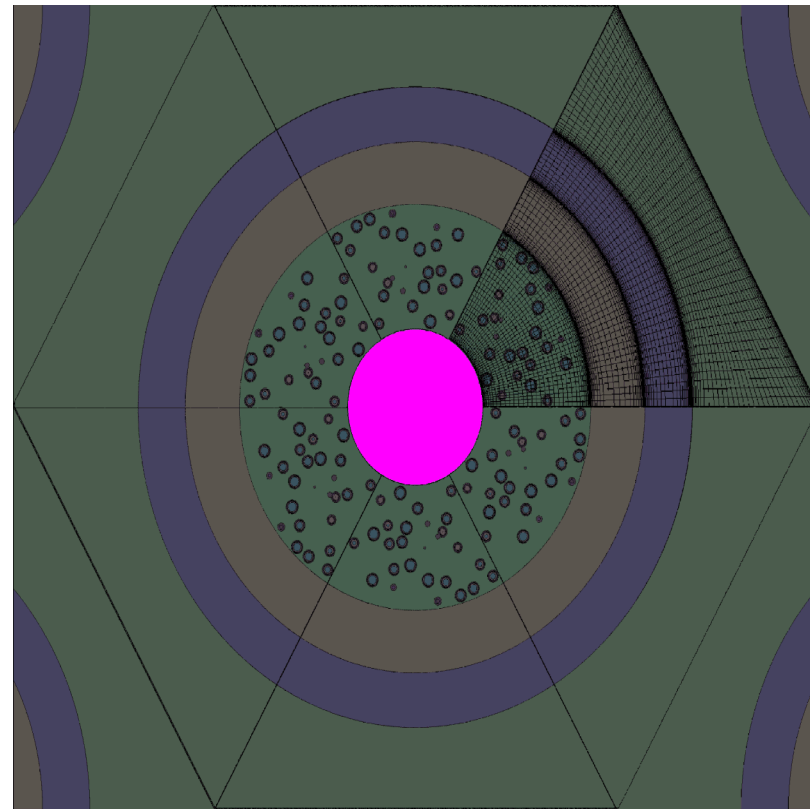
After modification



Serpent temperature meshes before and after modification of source code.



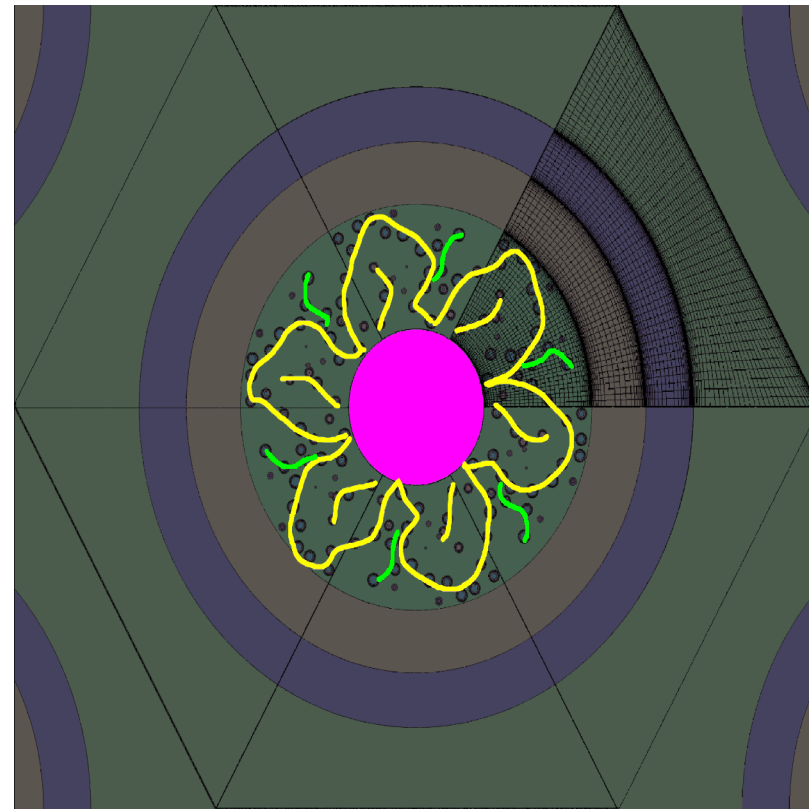
- In order to avoid unphysical results in OpenFoam due heat sources at *cyclic* boundaries, TRISO particles crossing the boundaries were deleted.
- TRISO particles that left were further rotated to keep the Serpent input consistent with OpenFoam.



Serpent geometry vertical cross-section with rotated
TRISO particles group.

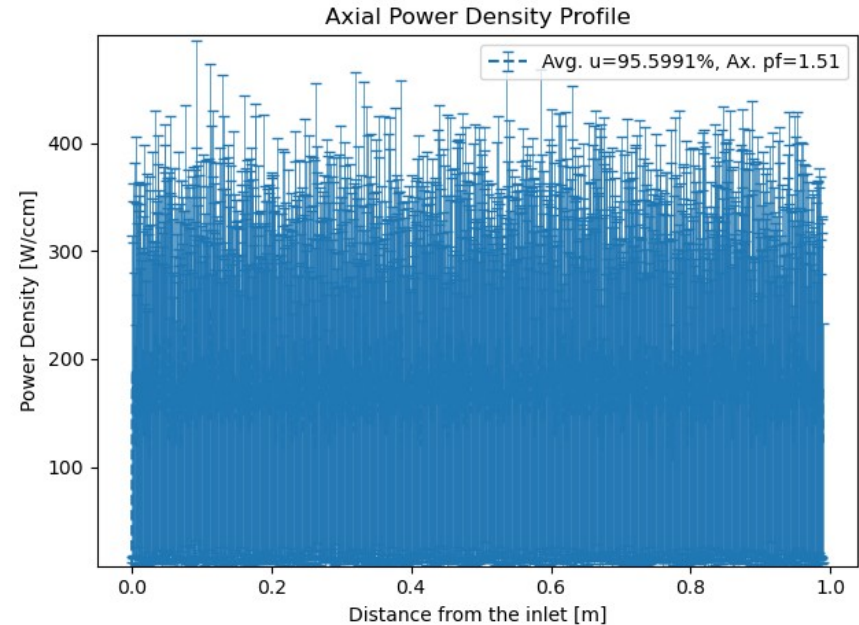
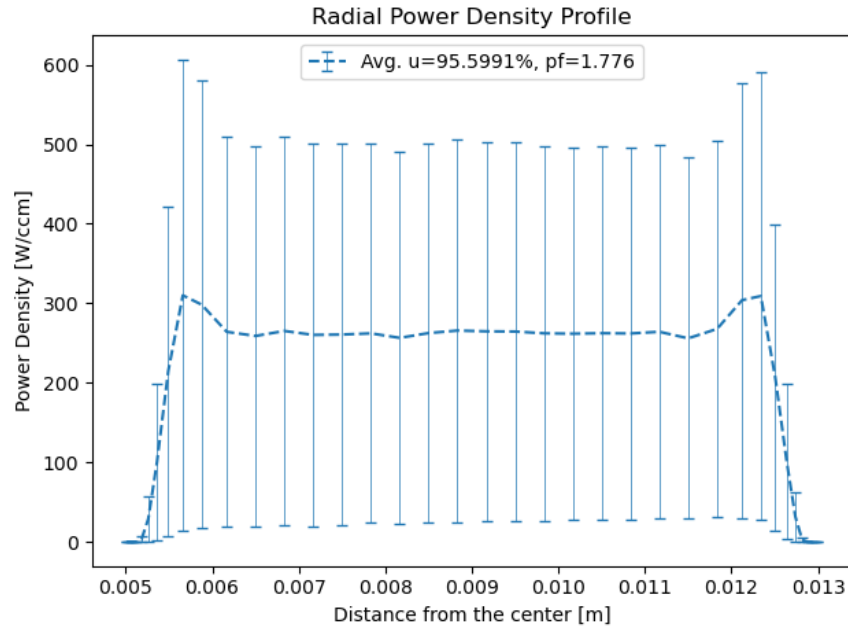


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Serpent geometry vertical cross-section with rotated
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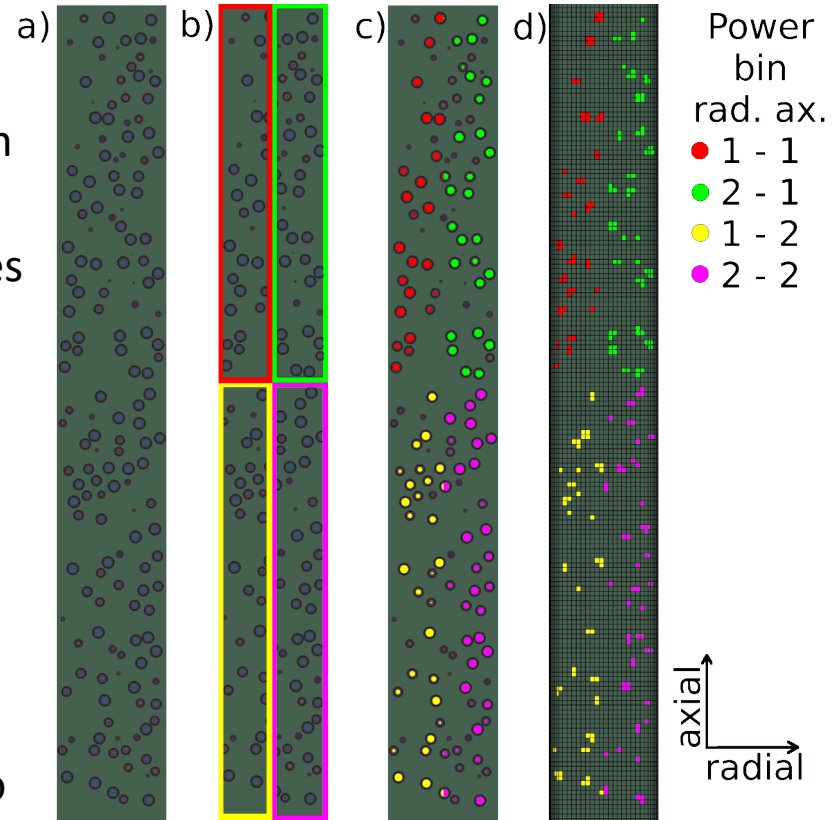
High uncertainties due to small space in cells – poor statistics in the Monte Carlo method. It is necessary to cluster TRISO kernels.



Mehodology towards power bins generation.

Power bin is a group of TRISO kernels for which average power is calculated

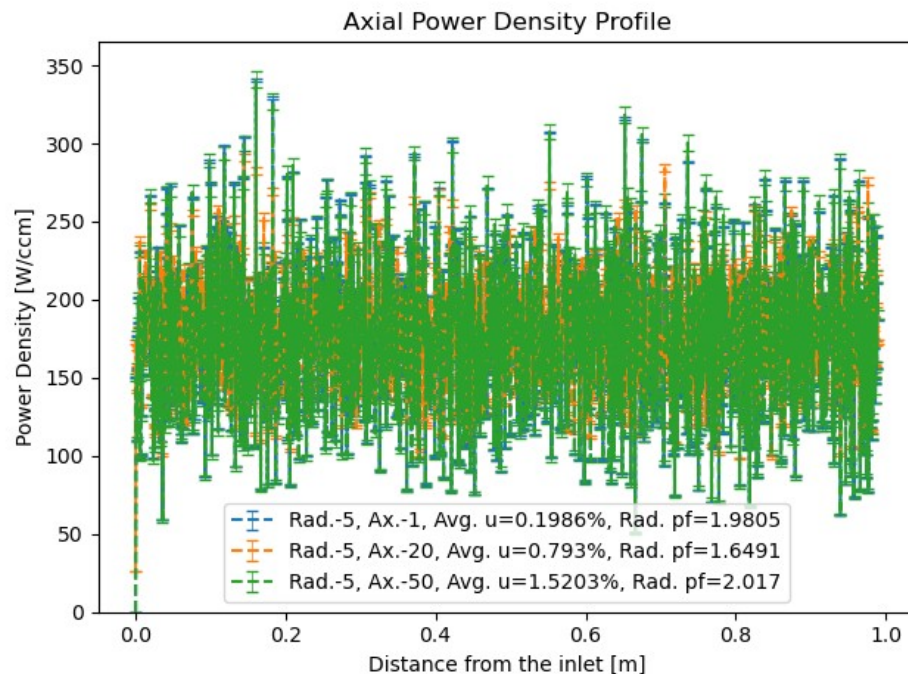
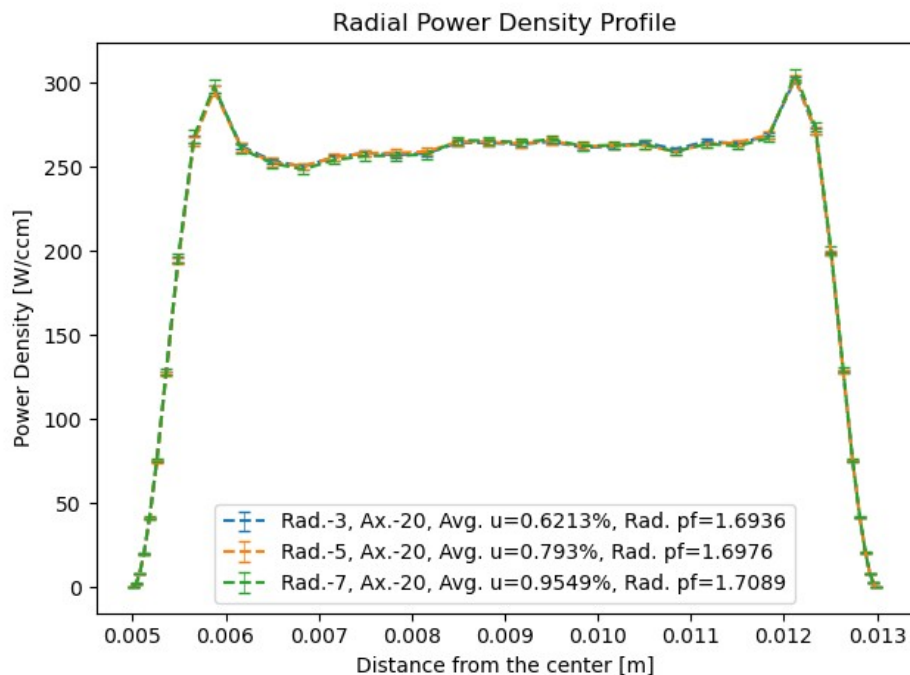
- a) Vertical fuel pellet cross-section with random TRISO particles distribution
- b) Division of the fuel compact into power zones according to their radial and axial position:
 - Radial zone 1, Axial zone 1 – red
 - Radial zone 1, Axial zone 2 – green
 - Radial zone 2, Axial zone 1 – yellow
 - Radial zone 2, Axial zone 2 – purple
- c) Adjustment of TRISO kernels to zones
- d) Power generated in each bin transferred do specific cells in OpenFoam model accoring to TRISO particles positions.





Current work - Serpent

- The more bins, the higher uncertainty
- pf – peaking factor, u - uncertainty

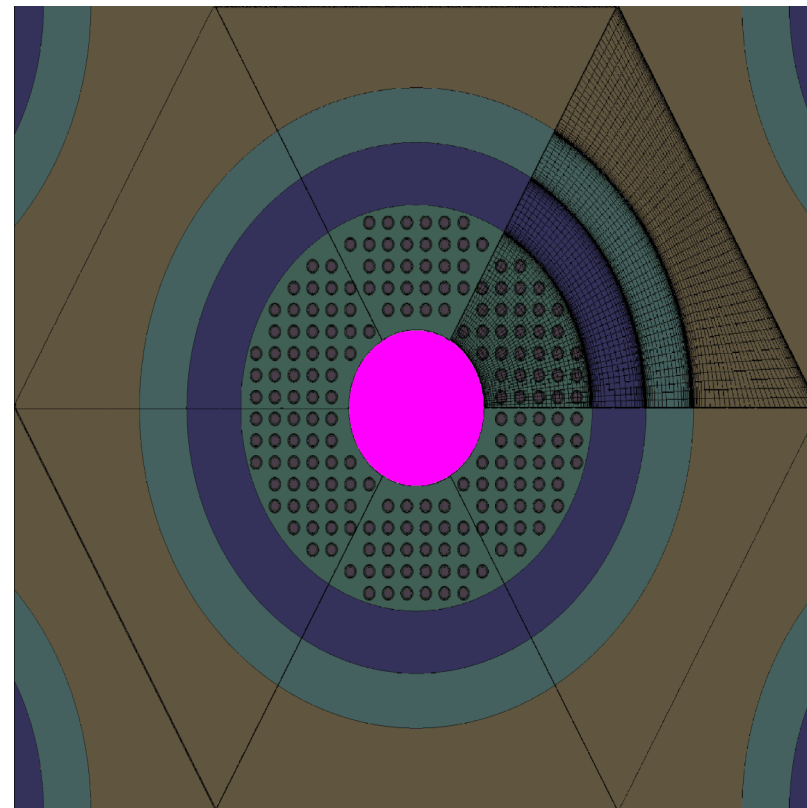
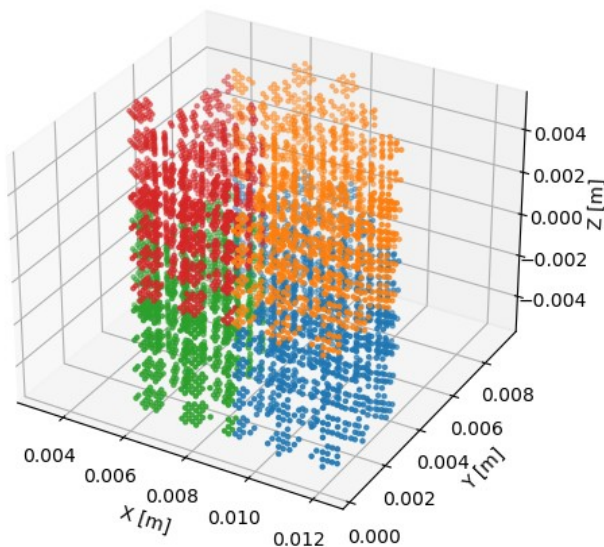




Current work - Serpent

- Random TRISO distribution cannot be modeled in MCB
- Power bins generated for regular TRISO lattice

TRISO cells position in OpenFoam mesh

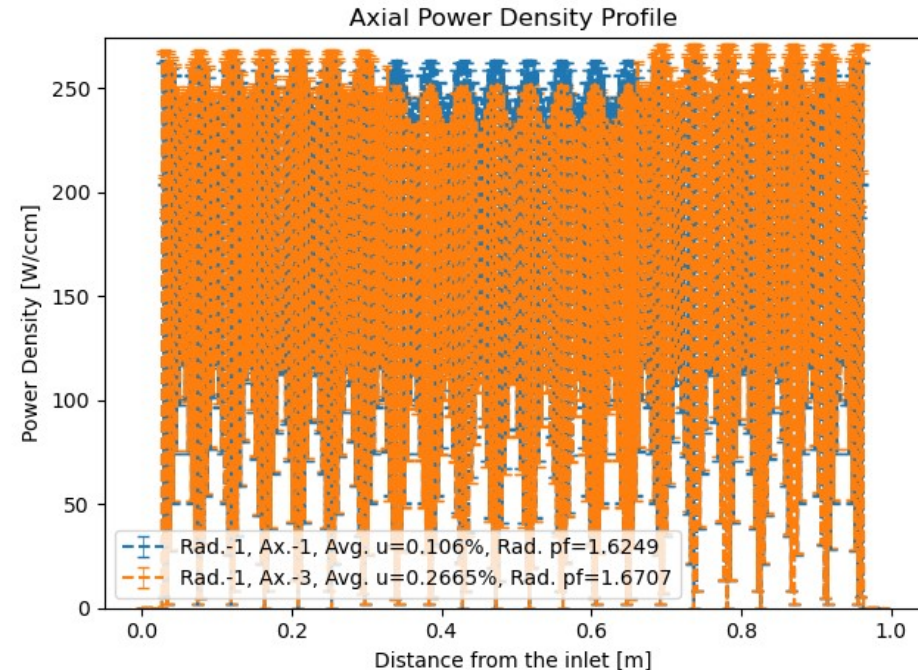
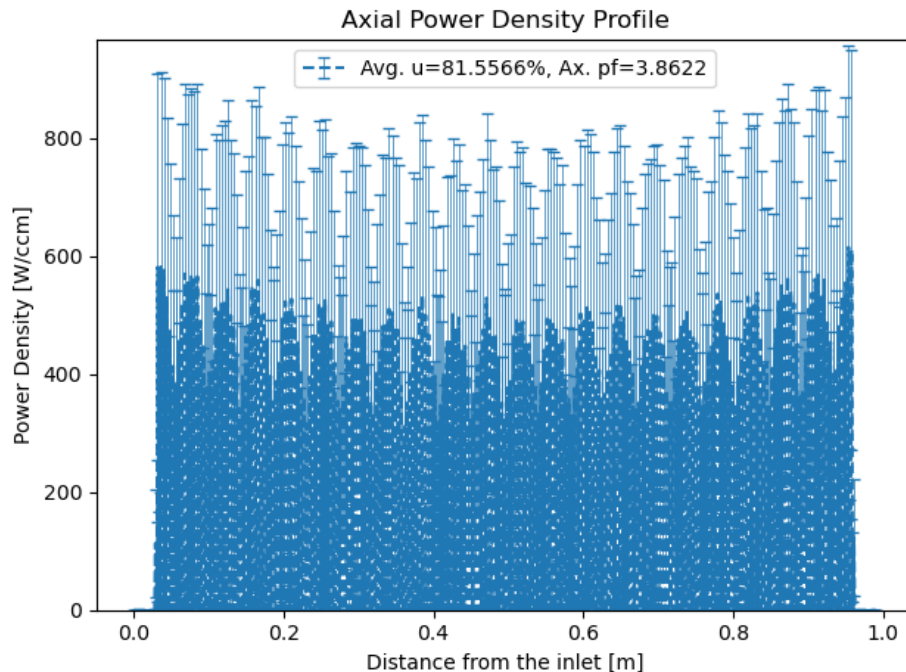


Serpent geometry vertical cross-section with regular TRISO lattice.



Current work - Serpent

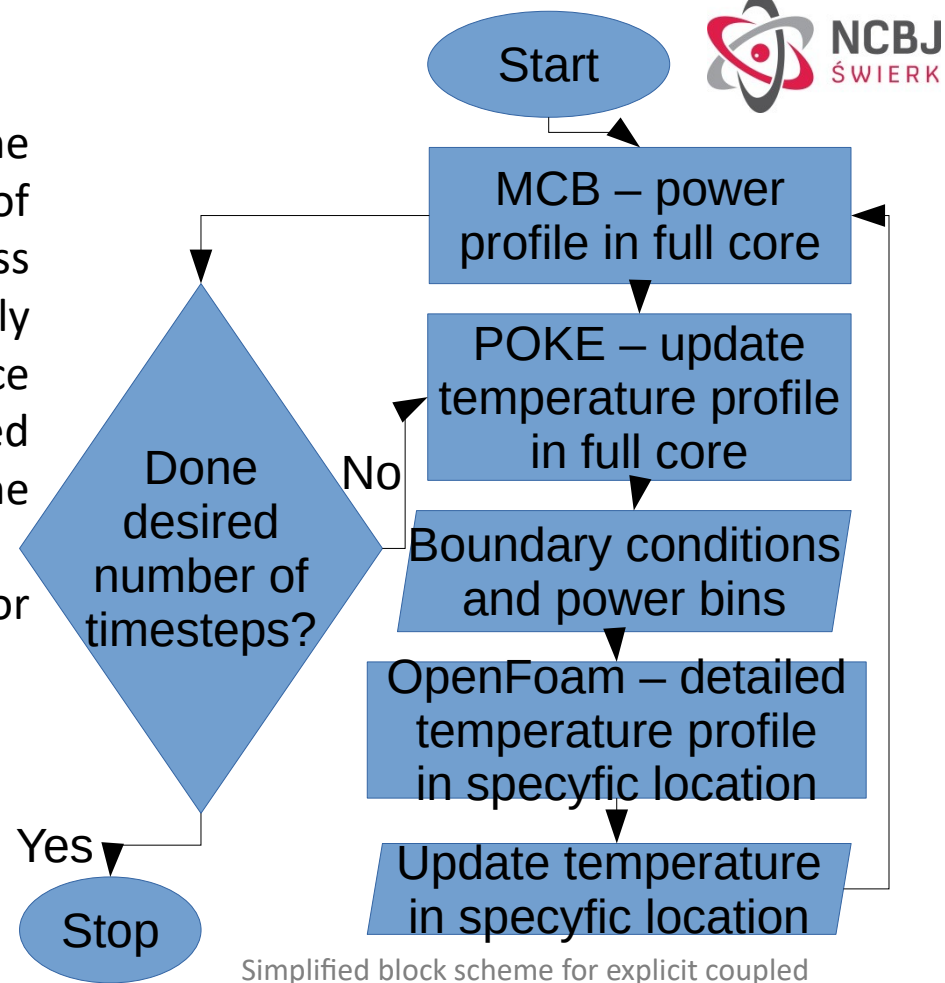
- Axial power profile has more regular character compared to random TRISO arrangement.
- pf – peaking factor, u - uncertainty



Coupling MCB+POKE+OpenFoam

NPP simulations using CFD alone are, in the majority of cases, beyond the capabilities of present computer hardware. Use of a less detailed, though less computationally demanding, system analysis code to produce initial and boundary conditions for a localized application of a CFD code appears to be the only practical alternative [5].

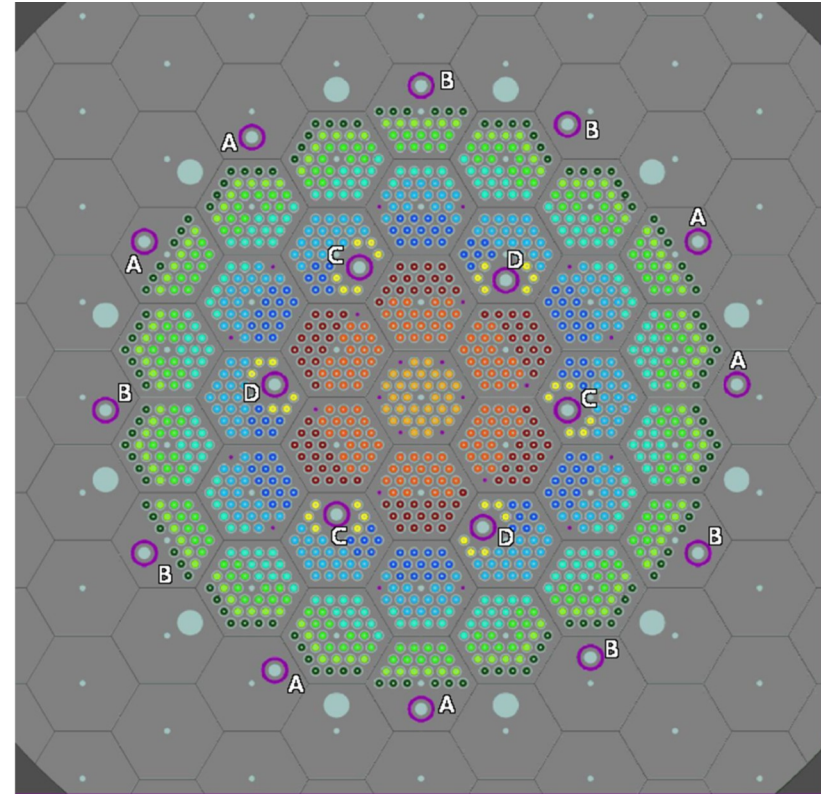
The above approach could be applied for MCB+POKE and OpenFoam CFD code.



Simplified block scheme for explicit coupled calculations

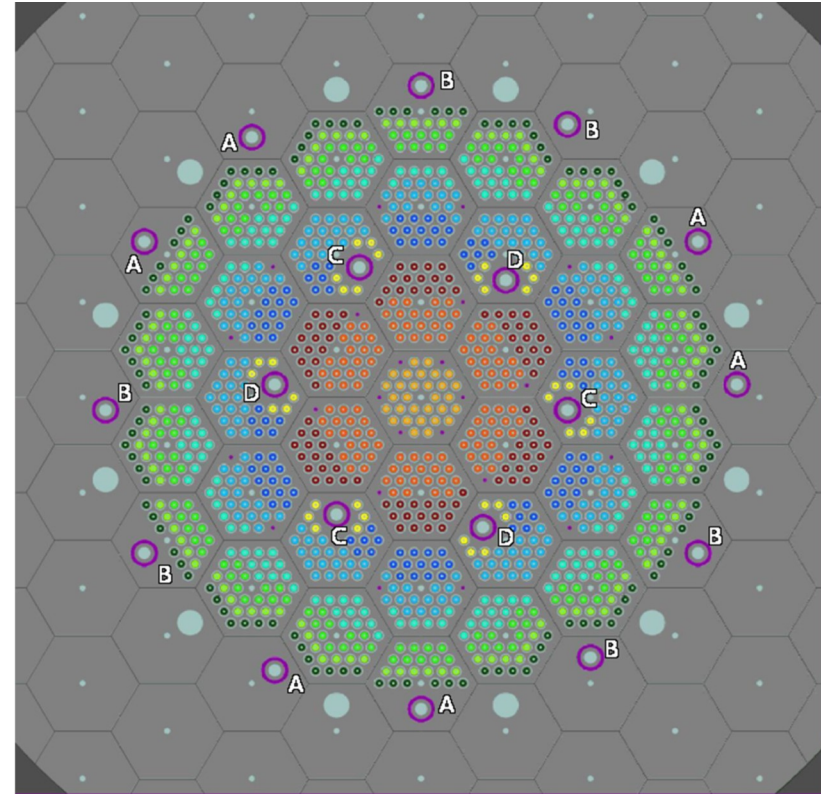
OpenFoam could work as a local support for MCB(neutronic and burnup)+POKE(system thermal-hydraulic), enhancing its applicability to simulate some accidental scenarios, e.g. loss of forced cooling in a cooling channel.

- OpenFoam would import power generation from MCB and other initial conditions from POKE
- After CFD calculations, new temperature profile would be updated in specific regions of the MCB model.
- Data transfer will be provided by Python script.



Go_HTR_J core configuration. Source: [4]

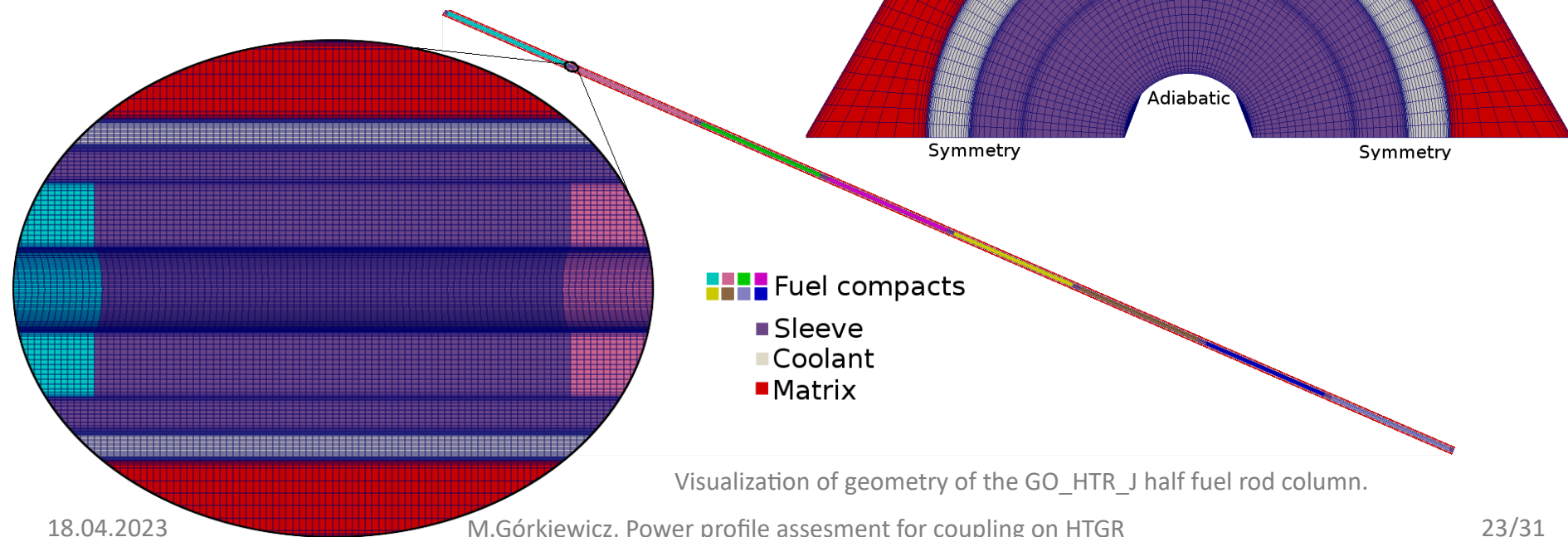
- 1/6 coolant channel OpenFoam is sufficient model for innermost burnable zone.
- In case of outermost fuel rods $\frac{1}{2}$ coolant channel model is necessary to include different temperatures from neighbouring zones (other burnable zone or reflector)
- Inclusion of CFD calculations enables one to analyse such case as reduced flow (due to graphite dust sedimentation).



Go_HTR_J core configuration. Source: [4]

Coupling MCB+POKE+OpenFoam – GO_HTR_J column

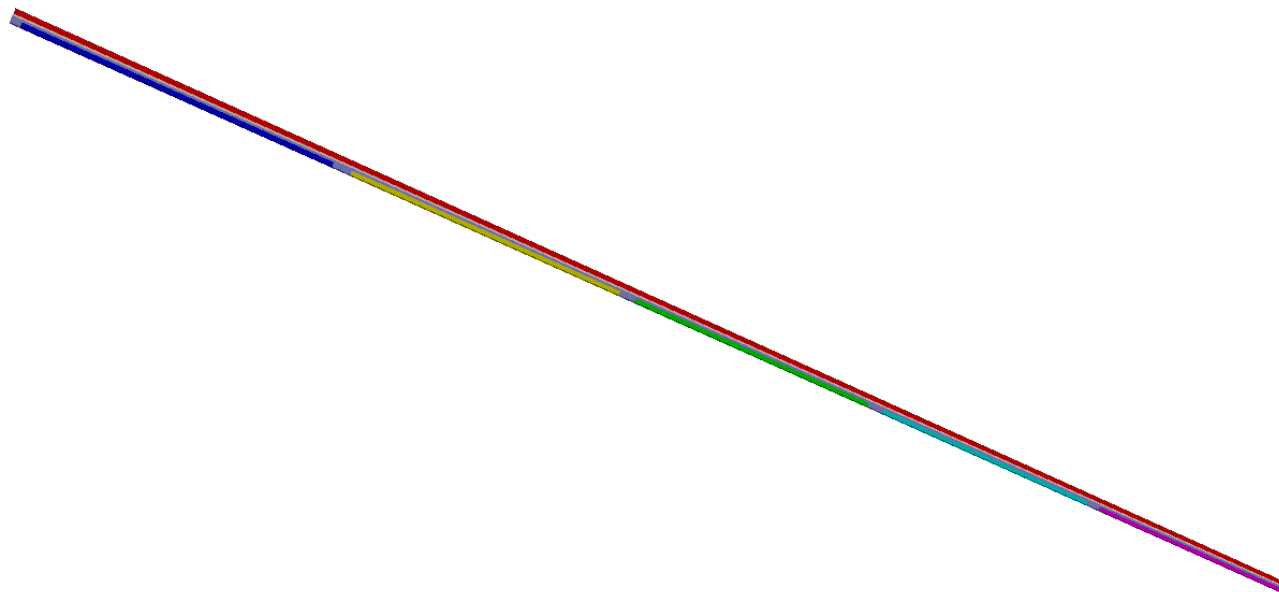
Broadened geometry set to apply 3 different boundary temperatures T1, T2 and T3



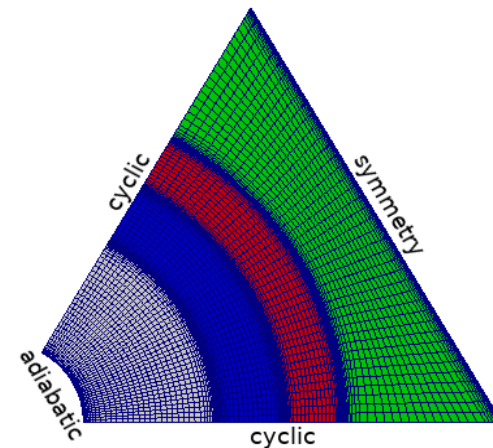


Coupling MCB+POKE+OpenFoam – OpenFoam HTTR column

Prepared geometry for HTTR type coolant channel through entire fuel block column for validation purposes.



Visualization of geometry of the HTTR fuel rod column

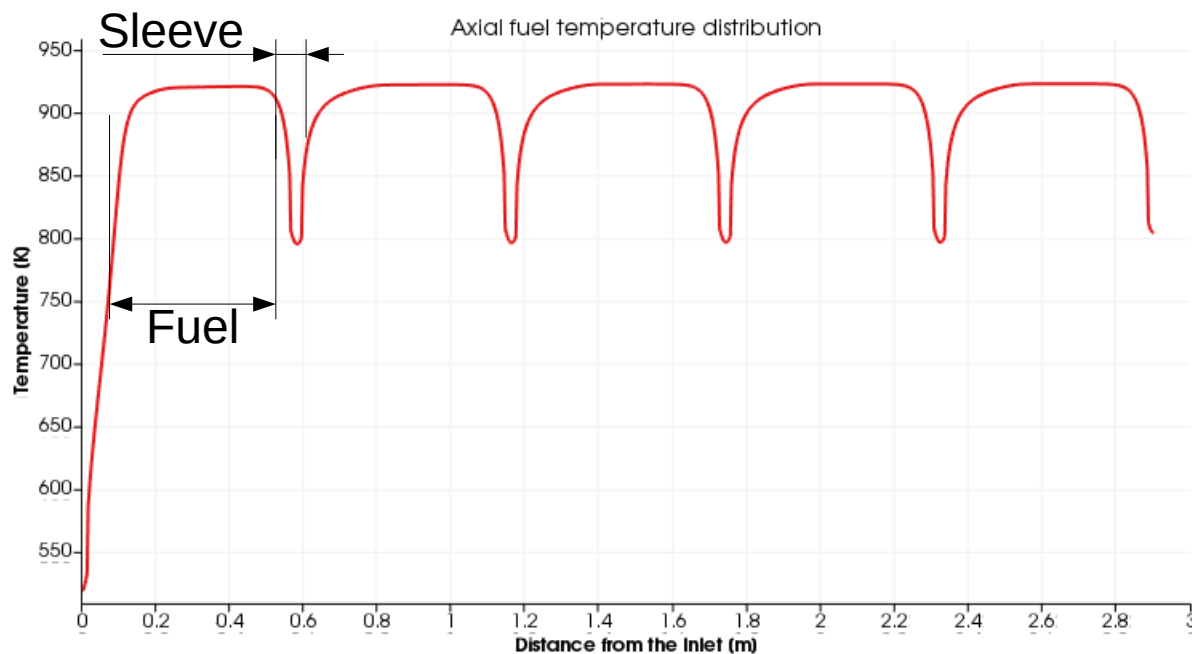




Coupling MCB+POKE+OpenFoam – OpenFoam column model

Preliminary results for uniform power generation.

- The highest temperatures occurs in fuel compacts
- Visible impact of sleeve parts dividing fuel rods

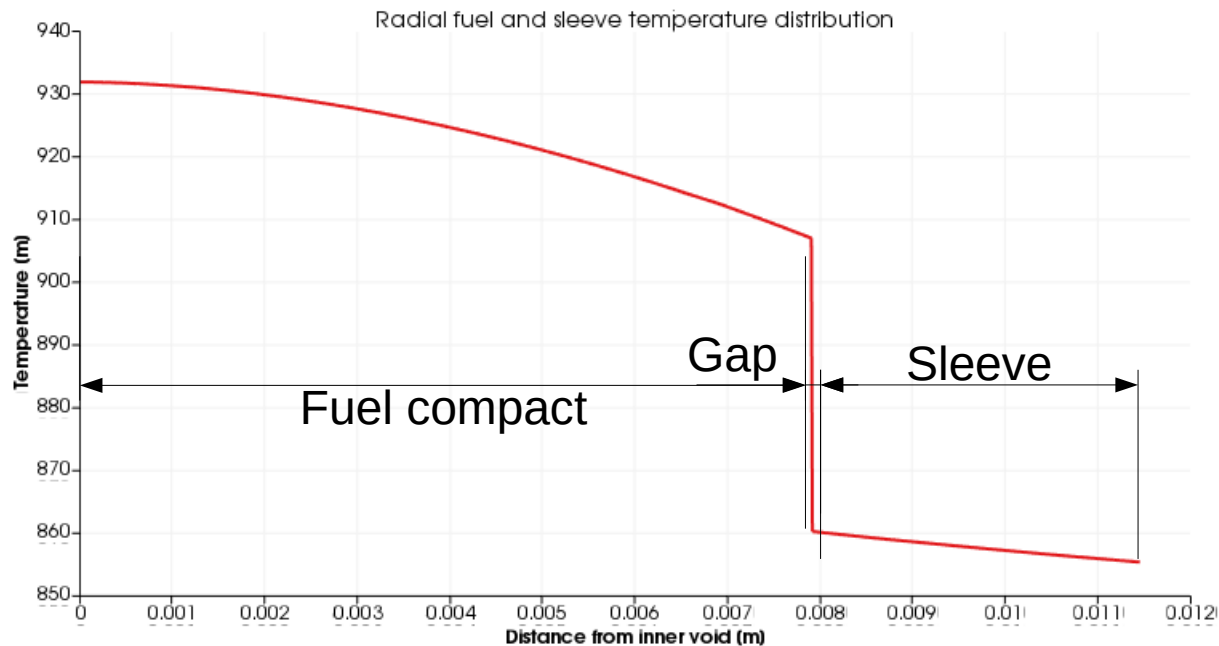
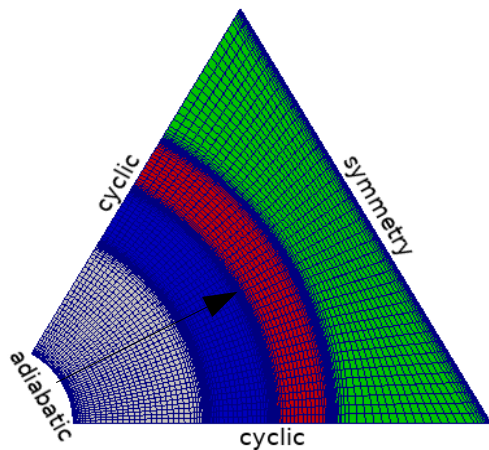




Coupling MCB+POKE+OpenFoam – OpenFoam column model

Preliminary results for uniform power generation.

- Visible impact of helium gap

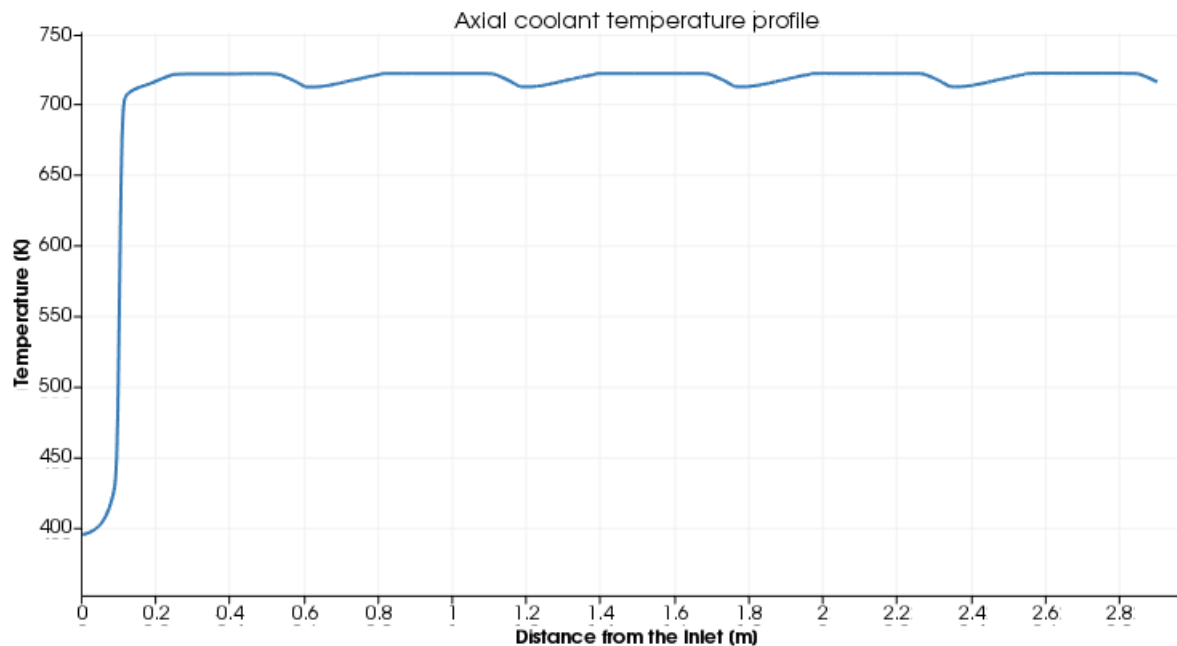




Coupling MCB+POKE+OpenFoam – OpenFoam column model

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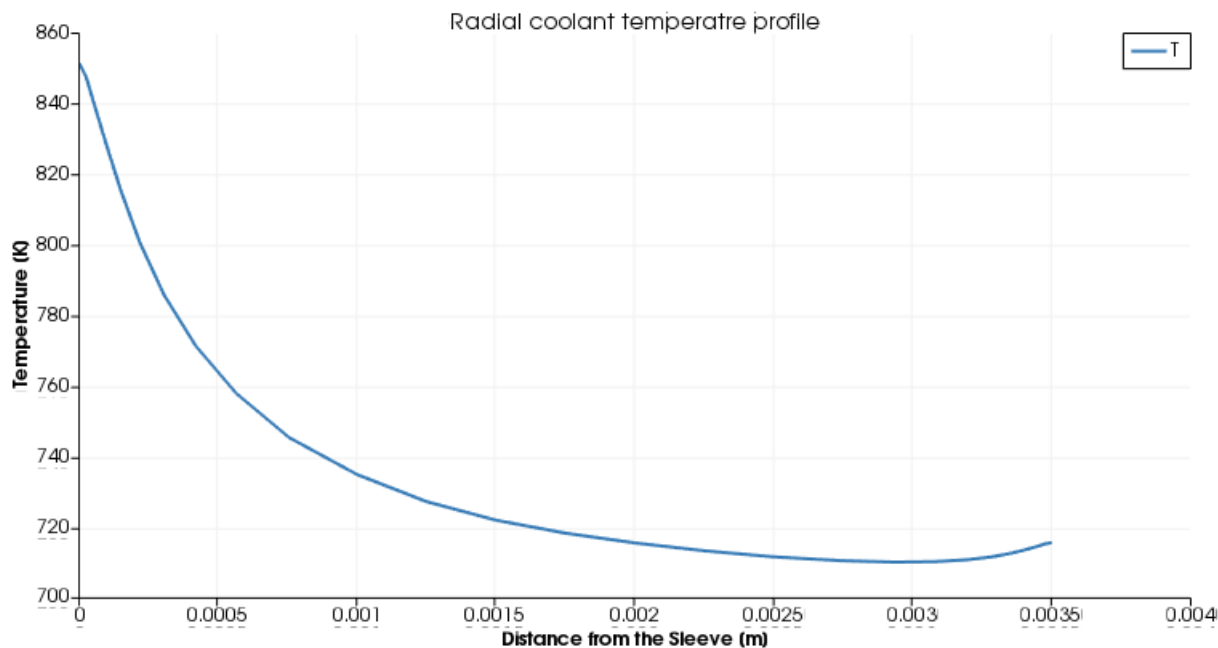
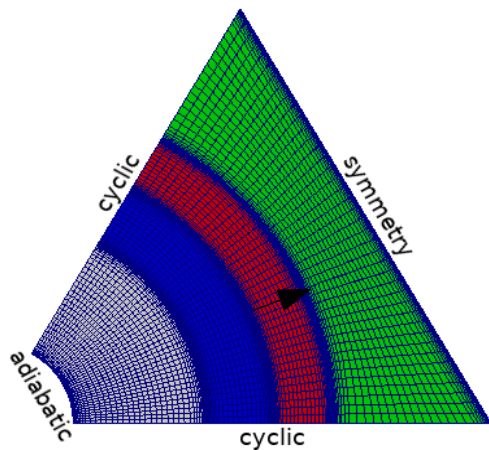




Coupling MCB+POKE+OpenFoam – OpenFoam column model

Preliminary results for uniform power generation.

- The highest temperatures at the sleeve wall



1. 3 kinds of OpenFoam models were created: 1/6 of a single fuel rod with reflective boundary condition, 1/6 of a single fuel column with reflective boundary conditions, half of a single fuel column with possibility of application 3 different temper boundary temperatures.
2. Methodology toward dividing TRISO kernels into power bins was developed and used for Serpent multi-physics interface in cases of random and regular TRISO distribution.
3. Coupled MCB+POKE calculations can be used for simulation of entire core, and OpenFoam can be used as support for detailed, localized analyses.
4. The methodology toward dividing TRISO kernels into power bins can be used for coupled MCB+POKE+OpenFoam calculations in case of regular TRISO lattice.
5. The above calculation are the core of my thesis.



1. Cetnar J. et. al.: *Advanced burnup assessments in prismatic HTR for Pu/MA/Th utilization using MCB system*, AGH, 2013
2. Cetnar J. et. al.: *The MCB Code for Numerical Modeling of Fourth Generation Nuclear Reactors*, Computer Science, vol. 16, p.329-350, 2015
3. Cetnar J. et. al.: *Przygotowanie różnych konfiguracji rdzenia pryzmatycznego reaktora HTGR na potrzeby analizy ekonomicznej*, AGH, 2020
4. Górkiewicz M., Cetnar J., *Flattening of the Power Distribution in the HTGR Core with Structured Control Rods*, Energies, 2021, 14, 7377
5. Summary Review on the Application of Computational Fluid Dynamics in Nuclear Power Plant Design, IAEA Nuclear Energy Series No. NR-T-1.20
6. https://serpent.vtt.fi/mediawiki/index.php/Multi-physics_interface
7. https://serpent.vtt.fi/mediawiki/index.php/Coupled_multi-physics_calculations

Thank you for attention



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