Benchmarking, Verification, and Application of GeN-Foam toward Multiphysics Simulation of MSRs

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[1]Seaborg Technologies

YMSR Conference

Overview

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GeN-Foam

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1. Reproduce the results from a widely-recognized MSR benchmark
2. Perform a neutronic verification based on point-kinetic decomposition
3. Apply GeN-Foam to a full-core model of the CMSR

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Neutronics

Diffusion model applicable to liquid-fueled reactors:

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Diffusion model applicable to liquid-fueled reactors:

- Multigroup diffusion

$$\frac{1}{v_i}\frac{\partial \varphi_i}{\partial t} = \nabla D_i \nabla \varphi_i + \sum_j \nu \Sigma_{f,j} \frac{(1-\beta_{\text{eff}})}{k_{\text{eff}}} \varphi_j \chi_{p,i} - \Sigma_{r,i}\varphi_i + \sum_k \lambda_k C_k \chi_{d,i} + \sum_{j \neq i} \Sigma_{j \to i} \varphi_j$$

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- DNP concentration

$$\frac{\partial C_k}{\partial t} + \boldsymbol{\nabla} \cdot (\mathrm{u}_{\mathrm{D}} C_k) = \nabla \cdot (D_m \nabla C_k) + \frac{\beta_{\text{eff},k}}{k_{\text{eff}}} \sum_j \nu \Sigma_{f,j} \varphi_j - \lambda_k C_k$$

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- Energy

$$\frac{\partial \gamma \rho e}{\partial t} + \boldsymbol{\nabla} \cdot \big(\mathrm{u} \gamma (\rho e + p)\big) = \boldsymbol{\nabla} \cdot \big(\gamma k_T \boldsymbol{\nabla} \mathrm{T}\big) + \gamma \mathrm{F}_{ss} \cdot \mathrm{u} + \gamma \dot{\mathrm{Q}}_{ss}$$

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1. Introduction & Objectives
2. Governing Equations
3. MSFR Benchmark
4. Neutronic Verification
5. CMSR Application
6. Closing Remarks

The Benchmark

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- MSFR benchmark developed at CNRS with released results[1] from various participants (CNRS, TUD, PSI, PoliMi).

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  - 2-D square reactor with a moving lid on top
- Broken down into steps leading up to transient simulation

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Single Physics

- Fixed flow field
- Fixed flux distribution
- Temperature field computed with a heatsink of the form:

$$q'''(\mathrm{r}) = \zeta(T_{ext} - T(\mathrm{r}))$$

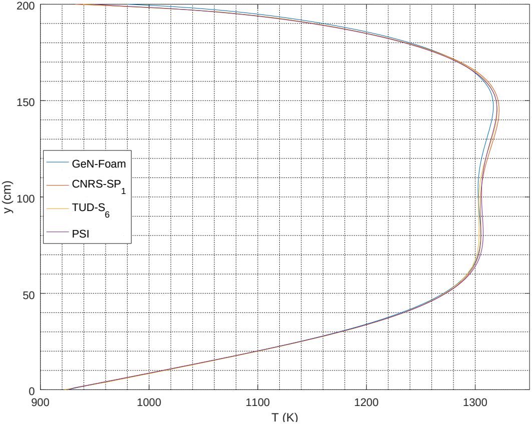

Figure: Axial temperature profile.

Steady-state Coupling

- Buoyant case
- Fully coupled: fission source influenced by flow field and vice-versa
- Slight difference caused by group constants

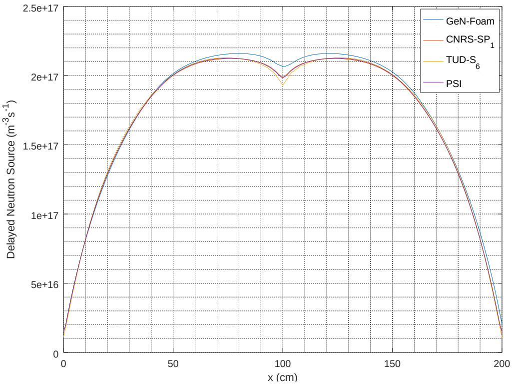

Figure: Distribution of delayed neutron source.

Transient Coupling

- Response to a sinusoidal heat transfer perturbation

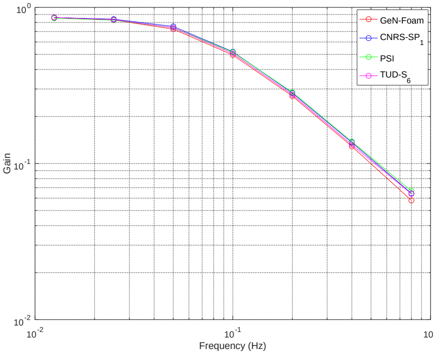

Figure: Relative gain.

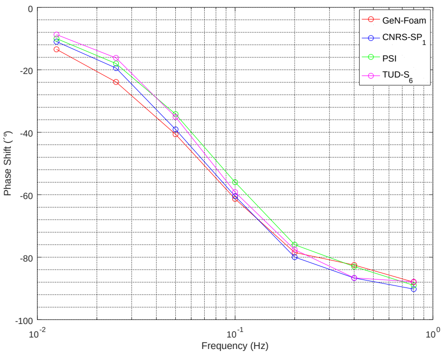

Figure: Relative phase.

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The Scheme

- Developed at Chalmers University of Technology[2]
- A general scheme for any reactor geometry or solution method
- Extensible to molten salt reactors

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- Extraction of point-kinetic component from simulation

$$\frac{\delta P(\omega)}{P_0} = \frac{\int\left[\frac{1}{v_1(\mathrm{r})}\phi^\dagger_{1,0}(\mathrm{r})\delta\phi_1(\mathrm{r},\omega) + \frac{1}{v_2(\mathrm{r})}\phi^\dagger_{2,0}(\mathrm{r})\delta\phi_2(\mathrm{r},\omega)\right]\mathrm{dr}}{\int\left[\frac{1}{v_1(\mathrm{r})}\phi^\dagger_{1,0}(\mathrm{r})\phi_{1,0}(\mathrm{r}) + \frac{1}{v_2(\mathrm{r})}\phi^\dagger_{2,0}(\mathrm{r})\phi_{2,0}(\mathrm{r})\right]\mathrm{dr}}$$

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- $\delta\rho(\omega)$ can be estimated from perturbation theory

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- Phase difference depends on the perturbation frequency

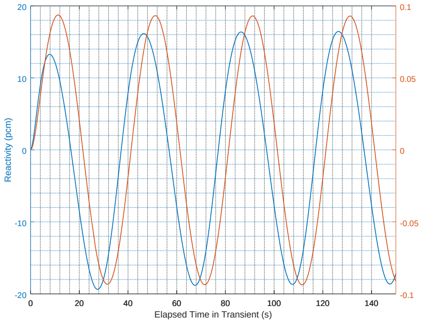

Figure: $f = 0.025$ Hz.

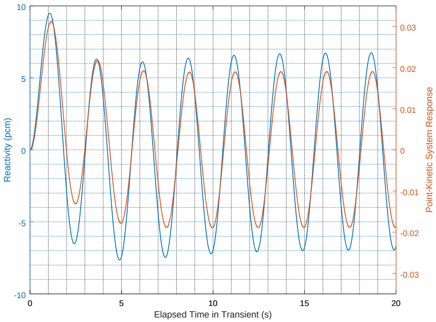

Figure: $f = 0.4$ Hz.

Implementation

- Across all perturbation frequencies

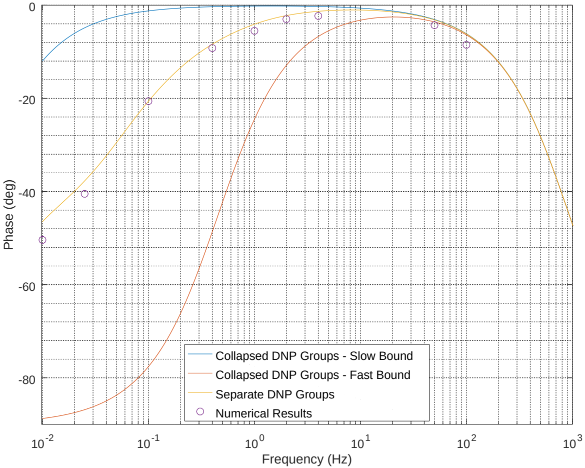

Figure: Phase of the point-kinetic transfer function.

Overview

The CMSR

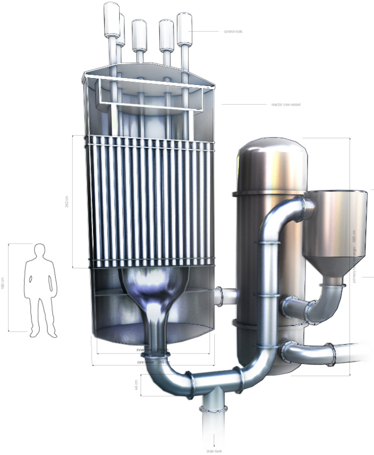

Figure: Conceptual rendering.

The CMSR

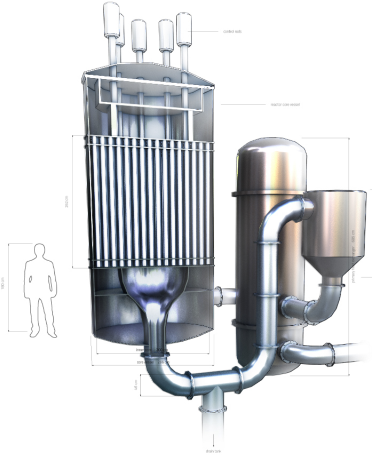

Figure: Conceptual rendering.

- 250 $\mathrm{MW_{th}}$

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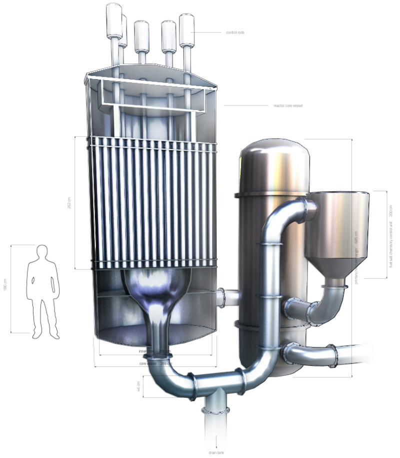

Figure: Conceptual rendering.

- 250 MW_{th}
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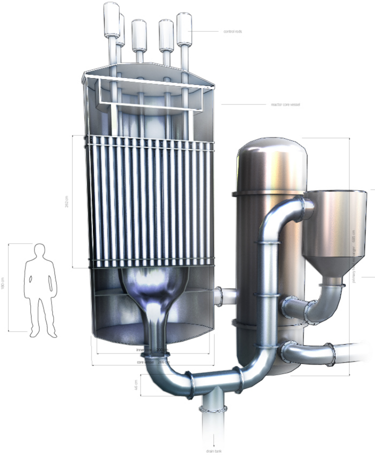

Figure: Conceptual rendering.

- 250 MW_{th}
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The CMSR

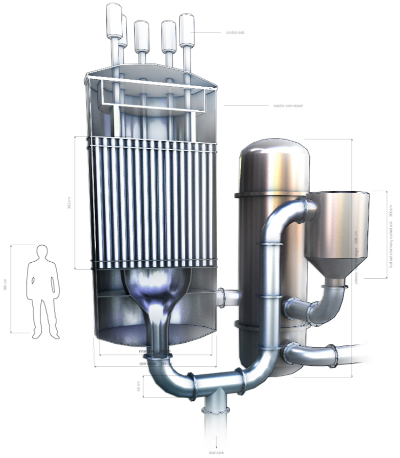

Figure: Conceptual rendering.

- 250 MW_{th}
- FUNaK fuel
- NaOH moderator
- Thermal spectrum

Model Description

- Homogeneous core as a porous medium
- Group constants generated in Serpent

Table: Basic parameters of the simplified CMSR core.

Parameter	**Value**	**Unit**
Power	250	MW_{th}
Height	2.0	m
Radius	1.2	m
Flow Rate	2900	kg/s
Porosity	0.41	
Inlet Temperature	823	K

Steady-state Solution

- Fully coupled solution

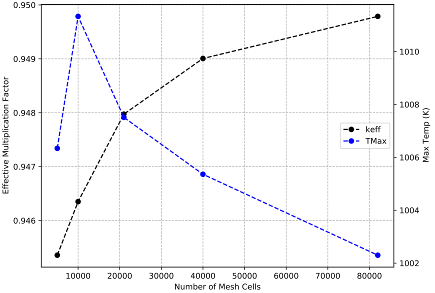

Figure: Mesh independence study.

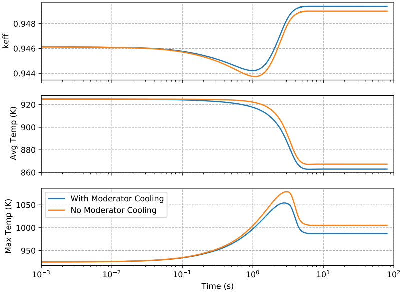

Figure: Steady-state with/without moderator cooling.

Steady-state Solution

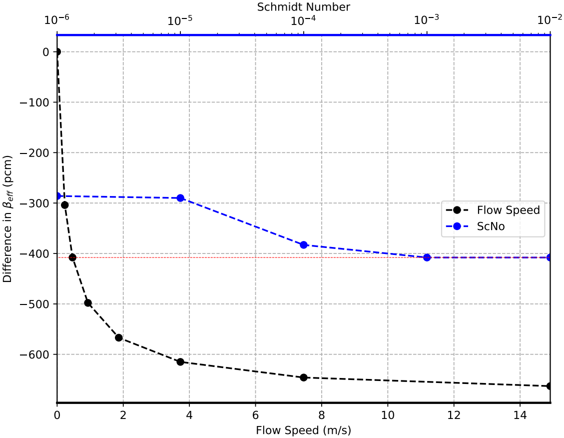

Figure: Change in β_{eff} depending on flow speed and Schmidt number.

Transient Simulation

- Response to postulated accidents

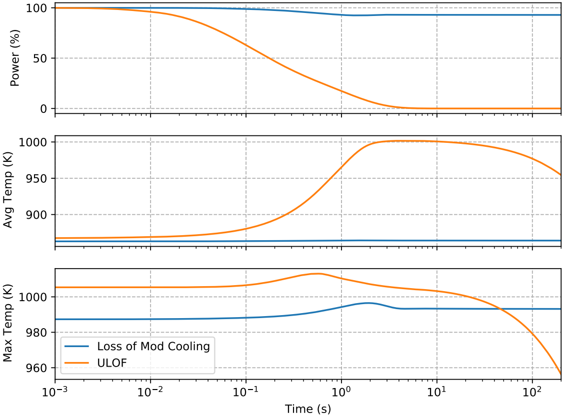

Figure: Heat exchange-based transients.

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- GeN-Foam under consideration for future simulations