Coupled neutronics and thermal-hydraulics numerical simulations of a Molten Salt Fast Reactor (MSFR)

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Molten Salt Fast Reactor

- Molten Salt
  - fuel = coolant
  - $LiF_4$ matrix
- Thorium fuel cycle
  - $^{232}Th/^{233}U$
- Fast spectrum
  - no solid moderator in the core

Objective ➔ estimate key reactor parameters at steady state:
- temperature hot spot
- effective fraction of delayed neutrons (precursors circulation)
Problematic:
- Complex flow patterns
- Interest in local values
- Conceptual design stage
- No experimental data

\[ \Rightarrow \text{CFD calculation} \]

\[ \Rightarrow \text{Monte Carlo neutronics calculation} \]

Thermal-hydraulics optimization

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MSFR - Outline

Coupling strategy
CFD - OpenFOAM
Neutronics - MCNP

Results
Neutronic parameters
Temperature and velocity distribution
MSFR - Coupling Strategy

- Fission power
- Neutronics
- MCNP
- Cross section
- Nuclear database
- OpenFOAM
  - Thermal-hydraulics
  - Temperature
  - Precursor circulation
- MAKXSF
  - ENDF-B7
Momentum Conservation Equation
\[
\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}(\overline{u}_j \overline{u}_i) - \frac{\partial}{\partial x_j}\left\{(v + v_t)\left[\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) - \frac{2}{3}\left(\frac{\partial \overline{u}_k}{\partial x_k}\right)\delta_{ij}\right]\right\} = -\frac{\partial}{\partial x_i}\left(\frac{\overline{p}}{\rho_o} + \frac{2}{3}k\right) + g_i\left[1 - \beta(T - T_0)\right]
\]

Continuity Equation
\[
\frac{\partial \overline{u}_j}{\partial x_j} = 0
\]

Energy Conservation Equation
\[
\frac{\partial \overline{T}}{\partial t} + \frac{\partial}{\partial x_j}(\overline{T} \overline{u}_j) = \kappa_{\text{eff}} \frac{\partial}{\partial x_k}\left(\frac{\partial \overline{T}}{\partial x_k}\right) + S_{\text{energy deposition}}
\]

Reynolds : \(~500\,000\)
RANS model : Realizable k-epsilon
Steady state calculations
Incompressible
Precursors circulation treated as a chemical specie

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Correspondence between neutronics and thermal-hydraulics geometry

Elementary cell: brick with curved surfaces

5 000 volumes

Precursors position considered as a neutron source term for MCNP

Density/cross section recalculated from CFD results

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The reactor can be considered as a prompt subcritical system with an exterior source of neutrons: decaying precursors.

We focus on the neutronic “prompt” flux resulting from a precursor decay, integrated over generations:

\[ \Phi = \Phi_1 + k_1^p \Phi_2 + k_1^p k_2^p \Phi_3 + \cdots + \left( \prod_{m=1}^{m_0-1} k_m^p \right) \Phi_m^0 + \left( \frac{\prod_{m=1}^{m_0} k_m^p}{1 - k_{eq}^p} \right) \Phi_{eq} \]

First generation of neutrons produced by the decaying precursors normalized per source.

Terms calculated using one simulation without discarded generation, up to the converged flux shape \( \Phi^0_m \).

Equilibrium flux value, calculated discarding firsts generations.
Objective = estimation of the margin to the prompt criticality: $1 - k_p = \tilde{\beta}$

$\Phi$: flux associated to the neutron shower induced by the decaying precursors (reactor neutron source)

$\beta \nu \Sigma_f \Phi$: represents the precursor production
Objective = estimation of the margin to the prompt criticality: $1 - k_p = \tilde{\beta}$

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Equilibrium condition, 1 decaying precursor creates 1 precursor:
Objective = estimation of the margin to the prompt criticality: \(1 - k_p = \beta\)

\(\Phi\) : flux associated to the neutron shower induced by the decaying precursors (reactor neutron source)

\(\beta \nu \Sigma_f \Phi\) : represents the precursor production

**Equilibrium condition, 1 decaying precursor creates 1 precursor:**

\[
\begin{align*}
\beta \nu \Sigma_f \Phi &= \langle \beta \nu \Sigma_f \Phi \rangle_1 + k_1^p \langle \beta \nu \Sigma_f \Phi \rangle_2 + k_1^p k_2^p \langle \beta \nu \Sigma_f \Phi \rangle_3 + \ldots \\
&+ \left( \prod_{m=1}^{m_0-1} k_m^p \right) \langle \beta \nu \Sigma_f \Phi \rangle_{m_0} + \left( \frac{\prod_{m=1}^{m_0} k_m^p}{1 - k_{eq}^p} \right) \langle \beta \nu \Sigma_f \Phi \rangle_{eq} \\
&= 1
\end{align*}
\]
The fuel enrichment is adjusted to obtain $\beta v \Sigma_f \Phi = 1$

- This enrichment corresponds to the steady state critical system
- The precursor circulation / spectrum effect are taken into account

The safety parameter can directly be deduced from:

$$1 - k_p = \tilde{\beta}$$
Coupling strategy
CFD - OpenFOAM
Neutronics - MCNP

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*Equilibrium condition: \( n_{\text{prod/src}} \beta = 1 \)
Equilibrium condition: \( n_{\text{prod/src}} \beta = 1 \)

\[
n_{\text{prod/src}} = \nu \Sigma f \Phi = \langle \nu \Sigma_f \Phi \rangle_1 + k_1^p \langle \nu \Sigma_f \Phi \rangle_2 + k_1^p k_2^p \langle \nu \Sigma_f \Phi \rangle_3 + \ldots + \left( \prod_{m=1}^{m_0} k_m^p \right) \langle \nu \Sigma_f \Phi \rangle_{m_0} + \left( \frac{\prod_{m=1}^{m_0} k_m^p}{1 - k_{eq}^p} \right) \langle \nu \Sigma_f \Phi \rangle_{eq}
\]

\[
\tilde{\beta} = 1 - k_p = 163 \pm 5 \text{ pcm}
\]

\[
1 - k_p \approx 50700 \beta
\]

\[
322 \pm 6 \text{ pcm}
\]

\[
\pm 0.5\%
\]

- MSFR - Coupling Results - \( \tilde{\beta} = 1 - k_p \) estimation

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MSFR - COUPLING RESULTS

U Magnitude
9 m/s
8
6
4
2
0.01

MCNP Temperature
767
750
725
700
675
650
627

T
770 °C
760
720
680
640
624

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MSFR - Coupling Results

- Symmetric
- Non-slip
- Recirculation

Middle plane

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CONCLUSION

* Steady state coupling dedicated to liquid fuel reactor
* High influence of recirculations on the temperature field in the core
* Significant influence of the precursors circulation on the effective fraction of delayed neutrons

PERSPECTIVES

* Modeling the heat exchangers with a porous media
* Unsteady calculations
CONCLUSION

- Steady state coupling dedicated to liquid fuel reactor
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PERSPECTIVES

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THANK YOU FOR YOUR ATTENTION ANY QUESTIONS?
\[
\sigma_{\text{cell}} = \frac{1}{tally_{\text{cell}}} \sqrt{\frac{1}{\text{nb}_{\text{simulation}}} \sum_{j=1}^{\text{nb}_{\text{simulation}}} \left( tally_{\text{cell},j} - \overline{tally_{\text{cell}}} \right)^2}
\]

24 million active particles

2.4 million active particles

amount of cells

1000-10000

100-1000

10-100

1-10

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\[ \langle \sigma_{cell} \rangle = \frac{1}{\sum_{cell} \sum_{tally_{cell}} (\sigma_{cell}tally_{cell})} \]

- energy deposition's standard deviation of the generation i vs the equilibrium value

24 million actives particles  2.4 million actives particles

amount of cells

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coupling schemes