Calculation of reactivity insertion in a generation IV Molten Salt Reactor

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Context

- Reactor specifications
  - Liquid fuel
  - Circulating fuel

- Power generation reactor (3 GW) isogenerator
  - Th/U, fluoride salt (TMFR)
  - U/Pu, chloride salt (PMCR)

- Study of hypothetical reactivity insertion accidents
  - Lead to a power peak
  - Increase of the salt temperature

- Objectives:
  - Feedback on reactor design
  - Volume of the expansion tank
  - Draining upper time
Non-compressible phenomenology (MOSAICS)

- Non-compressible phase
  - Neutrons precursors transport
  - Draining
    - Triggering by overflow
    - \( \sim 100 \text{ s} \)

Start of the accident

Degraded state

- Beginning of the reactivity insertion
- Recompacktion by the bubbles evacuation

Nominal operation

Reactivity insertion

Power increase

Temperature increase

- Doppler effect
- Density effect

Salt dilatation

Drainning not triggered

Overflow: Triggering of the drain
Compressible phenomenology (COCCINELLE)

- Compressible phase
  - Increase of the temperature => Increase of pressure
  - Doppler neutronic feedback almost alone
    - Density when salt goes out of the core
  - Inertial phase when vaporization occurs

Nominal operation

Start of the accident

Degraded state

- Beginning of the reactivity insertion
- Recompaction by the bubbles evacuation

Reactivity insertion

Power increase

Temperature increase

Compressible phase

- Increase of the temperature
  => Increase of pressure

Doppler effect

Reactivity drop

Temperature and pressure increase

If pressure is too high

Mechanical damages on the vessel

Acoustic phase

Return of pressure wave

P > Psat
No vaporisation

P < Psat
Vaporisation

Mechanical damages on the expansion tank and/or the vessel

Inertial phase

Fuel salt
Vaporized fuel salt
Gas in the expansion tank
Reprocessing gas
Compressible criterion

- In order to chain both the calculations tools, a criterion has been developed.

- Flow is incompressible if:
  \[
  \frac{\delta \rho}{\rho} \ll 1
  \]

- In MOSAICS, the incompressible hypothesis is considered as wrong if:
  \[
  \frac{\delta P}{Q c^2} > 0.01
  \]

  \[
  \Rightarrow \frac{1}{Q c^2} \left| \frac{\alpha}{\beta} \right| \frac{dT}{dt} t_c > 0.01
  \]

- This criterion is calculated at each time step in MOSAICS.
Characterisation of the criterion
Objective

- The compressible phase is not easy to model
  - Often need a different calculation tool
  - Increase a lot transient calculation time
  - Need more calculation resources to reach the same fidelity than incompressible CFD calculations

- Characterize the developed criterion (MOSAICS alone)
  - What kind of reactivity insertion leads to a compressible phase
  - What reactor characteristic changes the behavior of the core
Objective

Two kinds of reactivity transients are studied:

- Ramp/Step
- The maximum value of the criterion calculated will be interesting
  - If the maximum is below the trigger: Does not lead to compressible
  - If the maximum is higher: Lead to a compressible phase
- This will permit to understand in what kind of transient the compressible phase have to be model
- After this characterization, compressible transient have to be performed to understand the differences in the transient
Results of reactivity insertion, dilatability sensitivity

- Calculation in the fluoride version of the MSFR reactor

- Step reactivity
  - All the maximums of criterion calculated are above 0.01
  - Increase the dilatability increase the max value

- Ramp reactivity →
  - Low power, higher value
  - Only for more than 1000 pcm in 0.1 s at low power
Results of reactivity insertion, dilatability sensitivity

- Calculation in the chloride version of the MSFR reactor

- All the maximums of criterion calculated are above 0.01

- Increase the dilatability increase the max value

Ramp reactivity →

- Low power, higher value

- Only for more than 600 pcm in 0.1 s at low power
The calculations show that:

- Steps: the maximal value does not depend on the core power of the core
- Ramps: The lower the core’s power, the higher is the maximum value of the criterion
- At low power, it’s easier to have a compressible phase during a ramp reactivity transient

Differences between the Fluoride and the Chloride:

- For the same power, the maximal value of the criterion is higher in the Chloride than in the Fluoride version
- In both cases, the speed of sound is set at 1500 m/s
- The dilatabilities are:
  - -280 \( \cdot 10^{-6} \text{ K}^{-1} \) for the chloride
  - -210 \( \cdot 10^{-6} \text{ K}^{-1} \) for the fluoride
- The differences in the criterion probably come from these differences
Chaining of calculation tools

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Objective

- Reactivity transient with and without compressible phase
  - Comparisons and estimation on how important is the compressible calculation
    - What is the impact of the compressible transient in term of safety
    - Is the transient really different with the compressible phase than without?
  - Study the impact of the criterion and the impact of the trigger value

- Variation of the core’s properties:
  - Variation of the Doppler effect value to quantify its impact on the neutronic power and the temperature increase

- Study the impact of dilatability on reactivity transient:
  - What is the impact of the dilatability on the transient?
  - How the reactor parameters impact the behavior of the transient
Results: Doppler variation

- Fluoride MSFR, at 3 GW power, 400 pcm step reactivity

- The lower the Doppler effect, the higher the neutronic power is calculated

Mean temperature →

- The Doppler effect strongly impacts the mean temperature
- The compressible phase also

Normalized power
Results: Doppler variation

- Fluoride MSFR, at 3 GW power, 400 pcm step reactivity

- The lower the Doppler effect, the higher the neutronic power is calculated

Without compressible phase

Energy difference with BE

- A variation of 1 pcm/K on the Doppler effect induce around 1 and 2 GJ of differences in the neutronic energy deposit
Results: Criterion variation

- Fluoride MSFR, at 3 GW power, 400 pcm step reactivity

**Without compressible phase**

- When the trigger value decreases, the maximum calculated power increases

- Mean temperature →
  - Same than the normalized power
Results: Criterion variation

- **Fluoride MSFR, at 3 GW power, 400 pcm step reactivity**

  - When the trigger value decreases, the maximum calculated power increases.

  ![Graph showing normalized power](image)

  **Compressible phase trigger value**
  - 0.01
  - 0.015
  - 0.001
  - MOSAICS

  ![Graph showing energy difference with BE](image)

  **Compressible phase trigger value**
  - 0.015
  - 0.001

**Energy difference with BE**

- When the trigger is higher, 0.5 GJ are missed in the compressible phase and if the trigger is lower, less energy is deposited in the salt.
Discussion

- Reactivity transient with and without compressible phase
  - As expected, the neutronic power and the temperature increases are higher during the compressible phase than on a full incompressible calculation.

- Variation of the core’s properties:
  - When the Doppler effect decrease, maximum neutronic power and temperature increases are larger
Conclusions and Perspectives
Conclusion and perspectives

- The work on chaining MOSAICS and COCCINELLE is on a good way, some work still have to be done:
  - Chaining for ramp reactivity insertion has not been performed
  - Some questions about the vaporization are still studied

- Characterization of criterion:
  - The behavior of the core is different under ramp and step reactivity transients
  - The lower the power of the core, the more probable a reactivity transient will lead to a compressible phase
    - Step reactivity is not realistic
  - Compressible transient is not always important to model

- Transients with both of the calculation tools:
  - The compressibility is important for the presented calculation
  - The value of the trigger is important but the impact is not as strong as the Doppler effect for example
Thank you for listening
### Differences between chloride and fluoride salt

#### Neutronic feedback:

<table>
<thead>
<tr>
<th>Feed-back</th>
<th>U/Pu - Cl</th>
<th>Th/U - F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doppler [pcm.K(^{-1})]</td>
<td>-0.6</td>
<td>-4.0</td>
</tr>
<tr>
<td>Density [pcm.m(^3).kg(^{-1})]</td>
<td>8.6</td>
<td>4.0</td>
</tr>
</tbody>
</table>

#### Thermodynamic properties:

- These values are estimations and can vary a lot with experiment & concept

<table>
<thead>
<tr>
<th>Properties</th>
<th>U/Pu - Cl</th>
<th>Th/U - F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg.m(^{-3})]</td>
<td>2771.7</td>
<td>4122.2</td>
</tr>
<tr>
<td>Heat capacity (Cp) [J.K(^{-1}).kg(^{-1})]</td>
<td>630.7</td>
<td>1602.3</td>
</tr>
<tr>
<td>Volume core [m(^3)]</td>
<td>30</td>
<td>9</td>
</tr>
<tr>
<td>Volume heat capacity [MJ.K(^{-1}).m(^3)]</td>
<td>1.7</td>
<td>17.0</td>
</tr>
<tr>
<td>Thermal intertia [MJ.K(^{-1})]</td>
<td>52.4</td>
<td>59.4</td>
</tr>
</tbody>
</table>
Compressible transition criterion
Compressible criterion

- Thanks to physicals considerations, the compressible transition criterion have been modified.

- The criterion is calculated into 2 steps:
  - Estimation of a pressure increase
  - Calculation of the criterion
    - \( \frac{\delta P}{\rho c^2} \ll 1 \)
    - \( P \): Pressure
    - \( \rho \): Mean density
    - \( c \): Speed of sound ~ 1500 m/s
  - This is a Mach number: \( v = \frac{\delta P}{\rho c} \)
  - The flow become compressible when \( \frac{\delta P}{\rho c^2} \ll 1 \) is not verified:
    - \( \frac{\delta P}{\rho c^2} > 0.01 \)

- The way to estimate \( \delta P \) changed
The modified criterion is calculated with the following pressure estimation:

\[ \delta P = \frac{\alpha}{\beta} \frac{dT}{dt} t_c \]

- \( \frac{dT}{dt} \): Maximum temperature variation
- \( \alpha \): Dilatability
- \( \beta \): Compressibility
- \( t_c \): Characteristic time

- Come from evolution of pressure rise at fixed volume

Here, \( t_c \) is the characteristic time of the physical phenomena.

\[ t_c = \frac{L_{\text{core}}}{c_{\text{sound}}} \]

- The temperature derivative for the calculation is the highest temperature derivative calculate in the whole core.
Now the evolution of the criterion follow the evolution of the power:
- Seems more physical

In this calculation, the criterion is not crossed