Numerical modelling of melting and solidification phenomena in MSR

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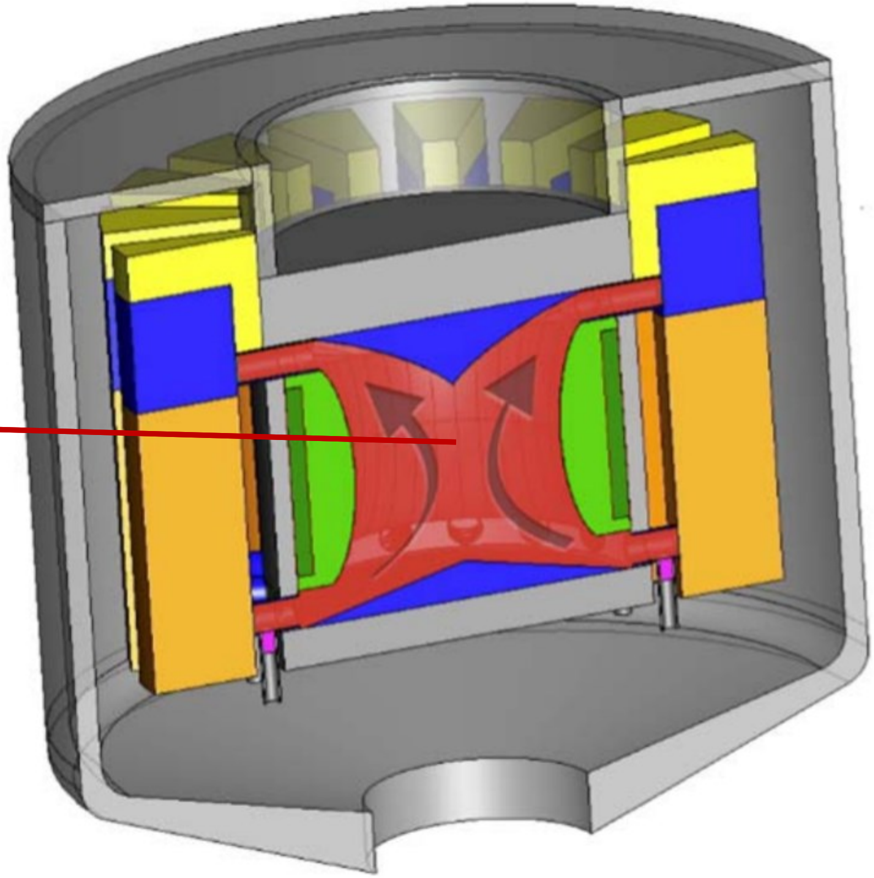
NRG/PoliMi

Molten Salt Fast Reactor

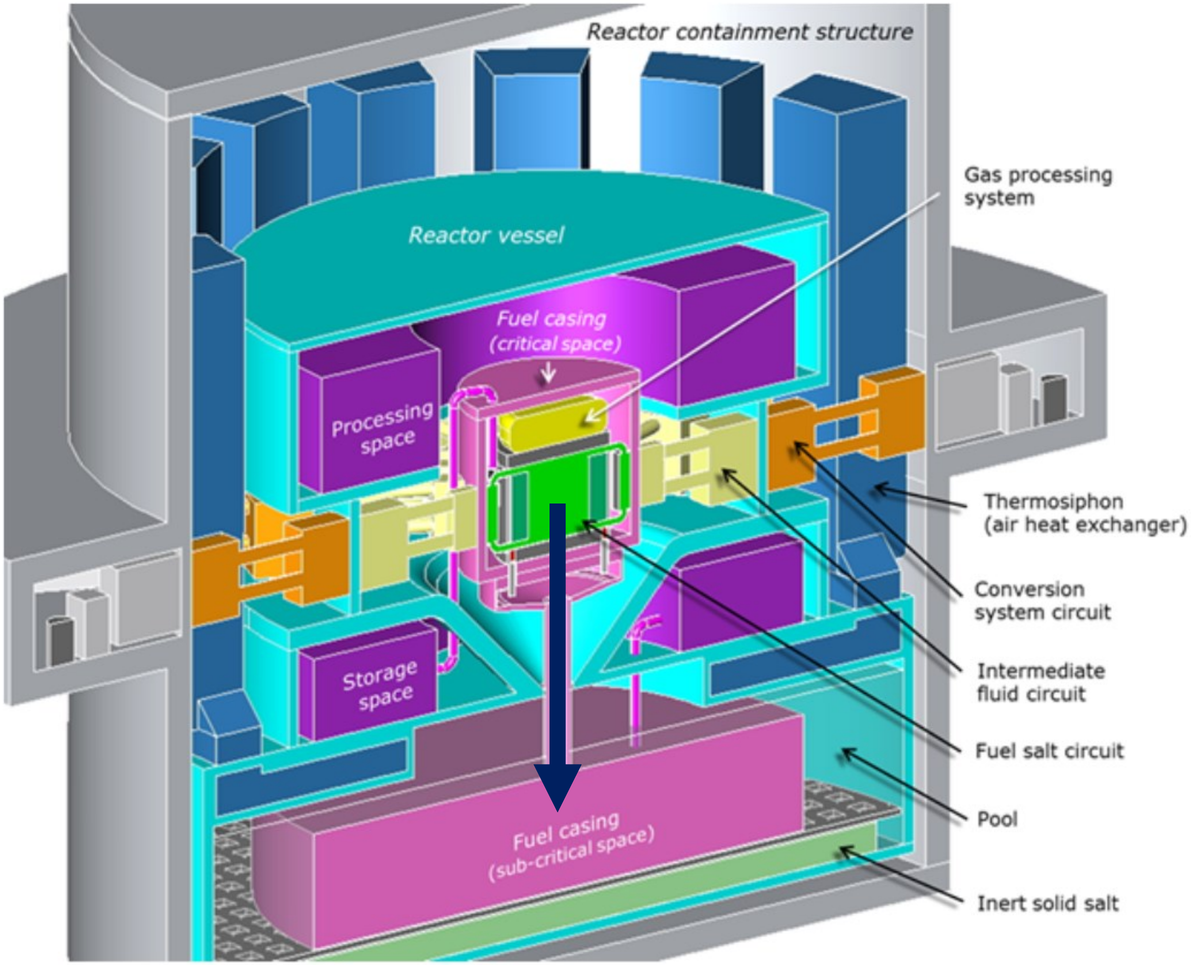
Liquid Fuel



Molten Salt Fast Reactor

Fuel Drainage

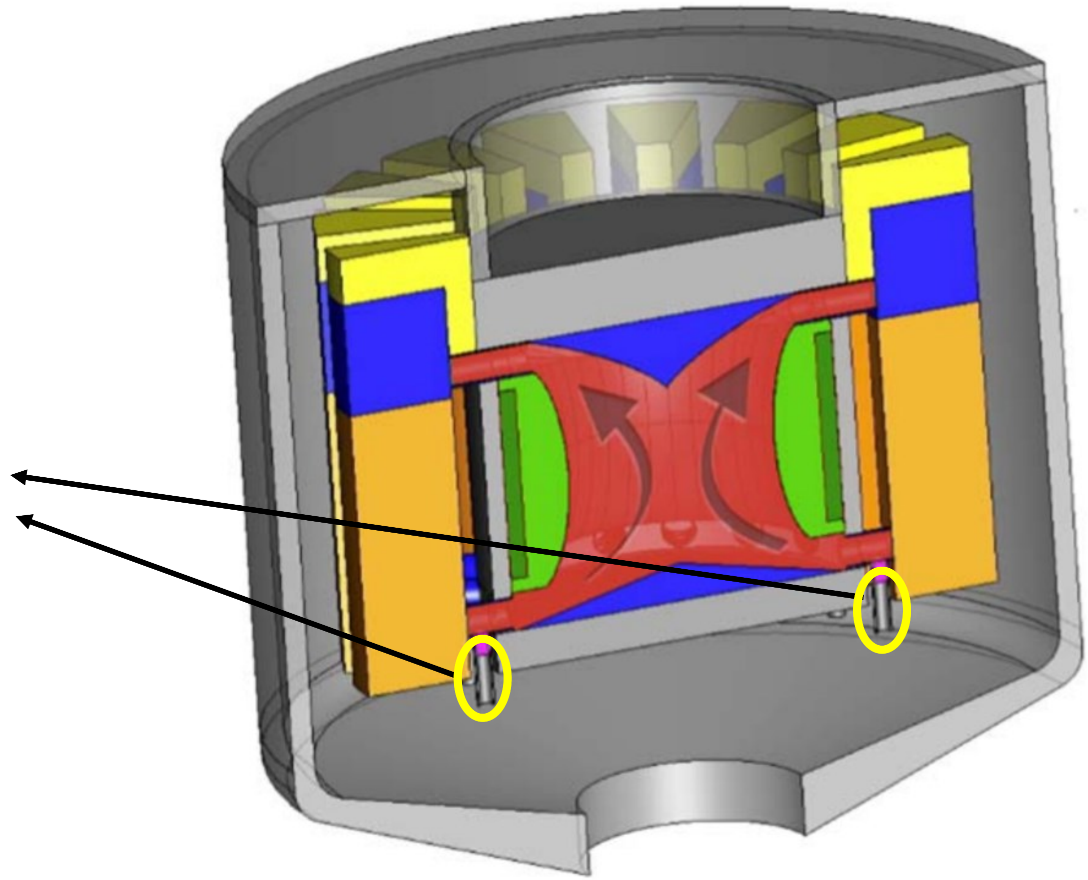
✓ Cooling
✓ Subcriticality



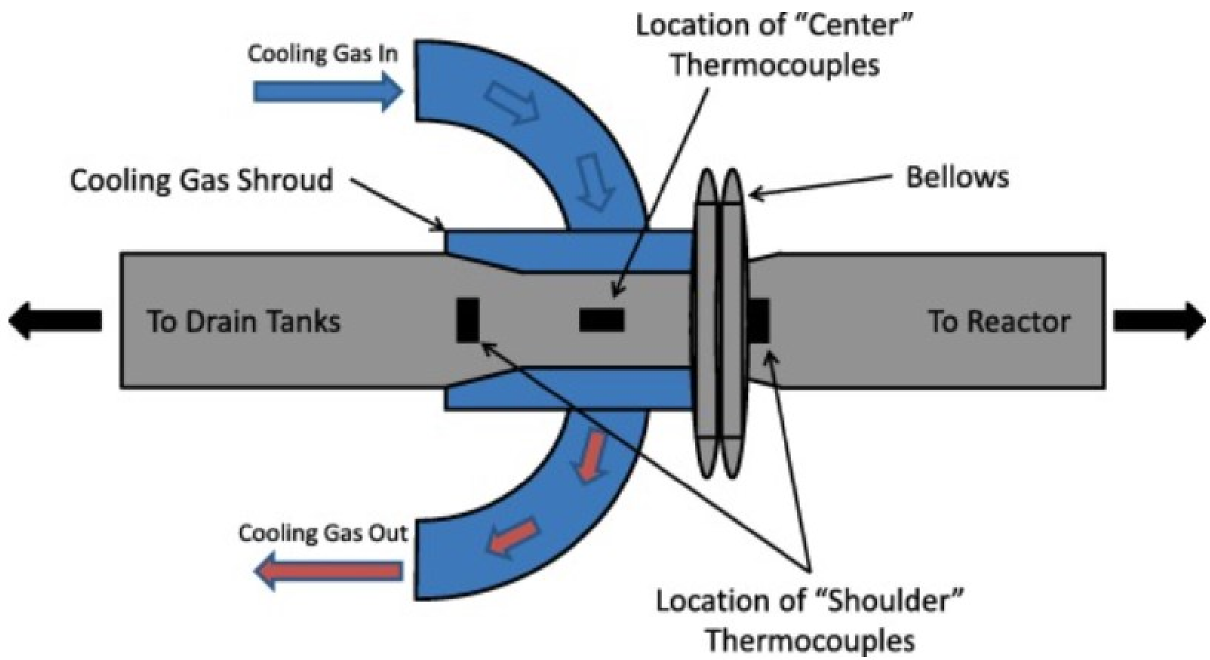
Freeze Valve

Freeze valves

Regulating the opening of the drainage system



Freeze Valve



- Compatibility with fuel salt
- Passivity? → SAMOSAFER

Overview

Objective:

Numerical modelling of melting and solidification phenomena in MSFR

Topics:

Choice of the model

Implemention in OpenFOAM

Verification

Applications & Future Work

The choice of numerical modelling

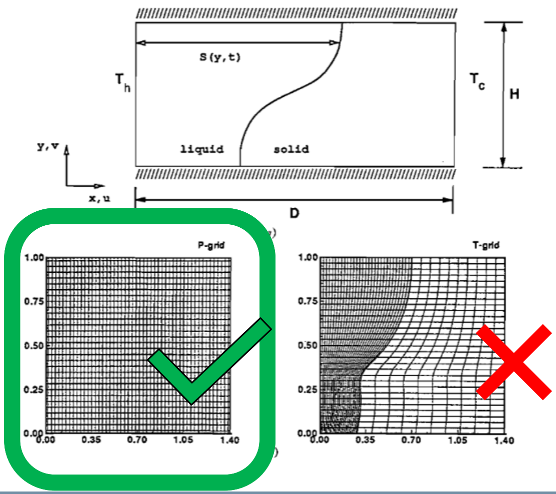
Our approach :

- FVM (OpenFOAM)
- Fixed Grid (No adaptive meshing)
- Continuum Mixture Model (Bennon & Incropera, 1987)

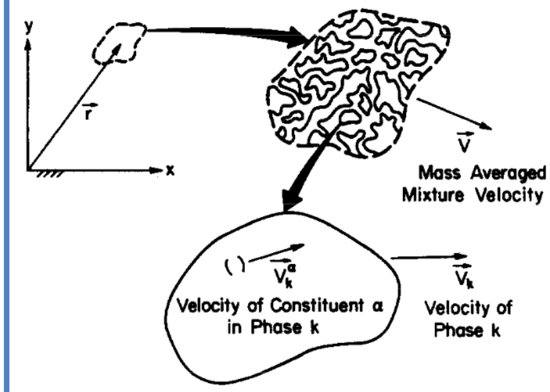
Finite Volume Method

Open∇FOAM

Fixed Grid



Continuum Mixture Model



Implementation

OpenFOAM®

Theoretical framework: Mixture Model (3 eq.s)

Equations:

$$\nabla \cdot (\vec{u}) = 0$$

$$\frac{\partial(\vec{u})}{\partial t} + (\vec{u} \cdot \nabla)\,\vec{u} = -\nabla(\tilde{p}) + \nabla \cdot (\nu_l \nabla \vec{u}) - A\,\vec{u}$$

$$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot (\rho h\,\vec{u}) = \nabla \cdot (k \nabla T)$$

Models:

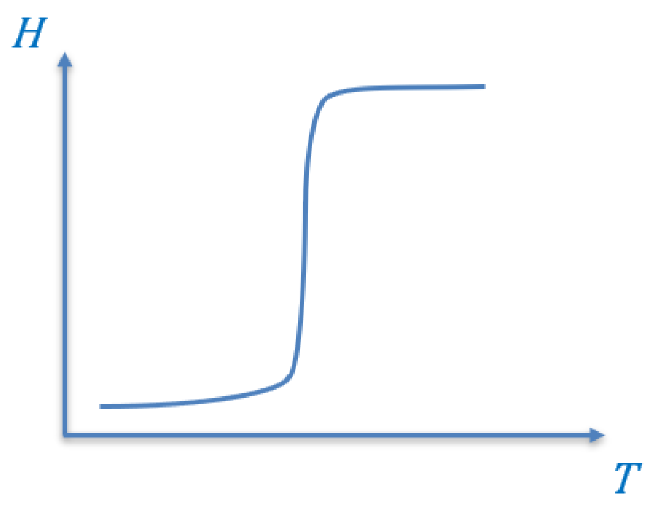
Latent Heat Modelling

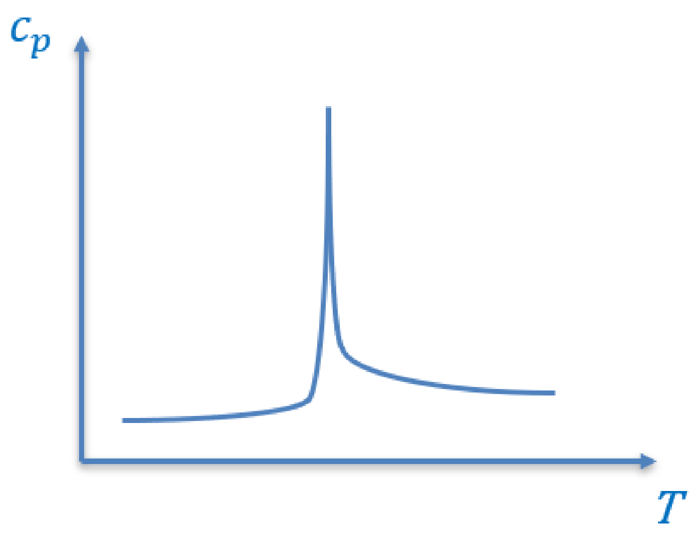
\+

Velocity Transition Modelling

Latent Heat Modelling

In phase transitions:





Latent Heat Models take into account the Latent Heat in the NRG equation.
We looked for:

- Temperature-based models (NRG eq solved for the temperature)
- A compromise between accuracy and speed

Latent Heat: a T-based approach

Latent Heat modelling

Temperature based
(Energy eq.)

Apparent
Heat Capacity
(AHC)

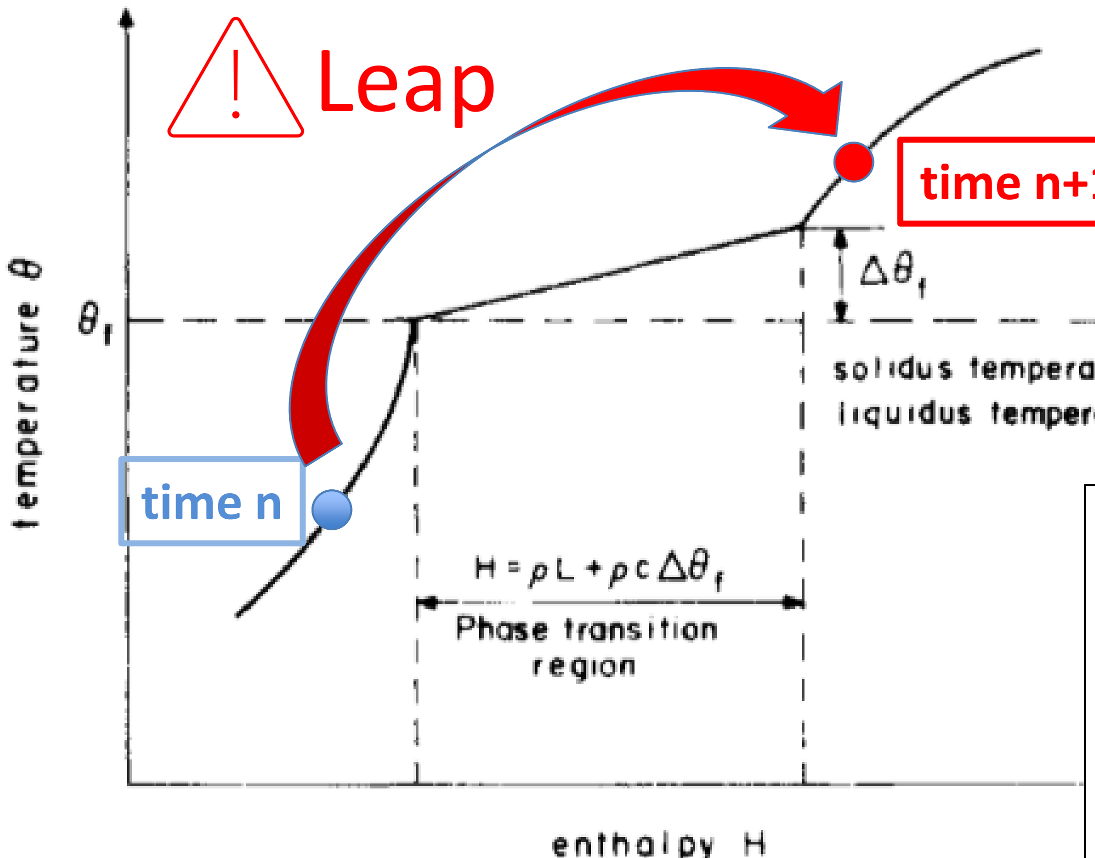
- ✓ Fast (non-iterative)
- × Can be inaccurate
- × Sensitive to arbitrary numerical parameters

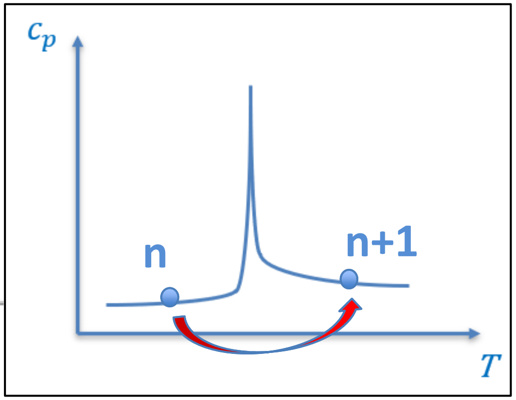
Source Term (ST)

- ✓ Accurate
- ✓ Not too sensitive to numerical parameters
- × Slow (iterative)

→ Hybrid Approach? ←

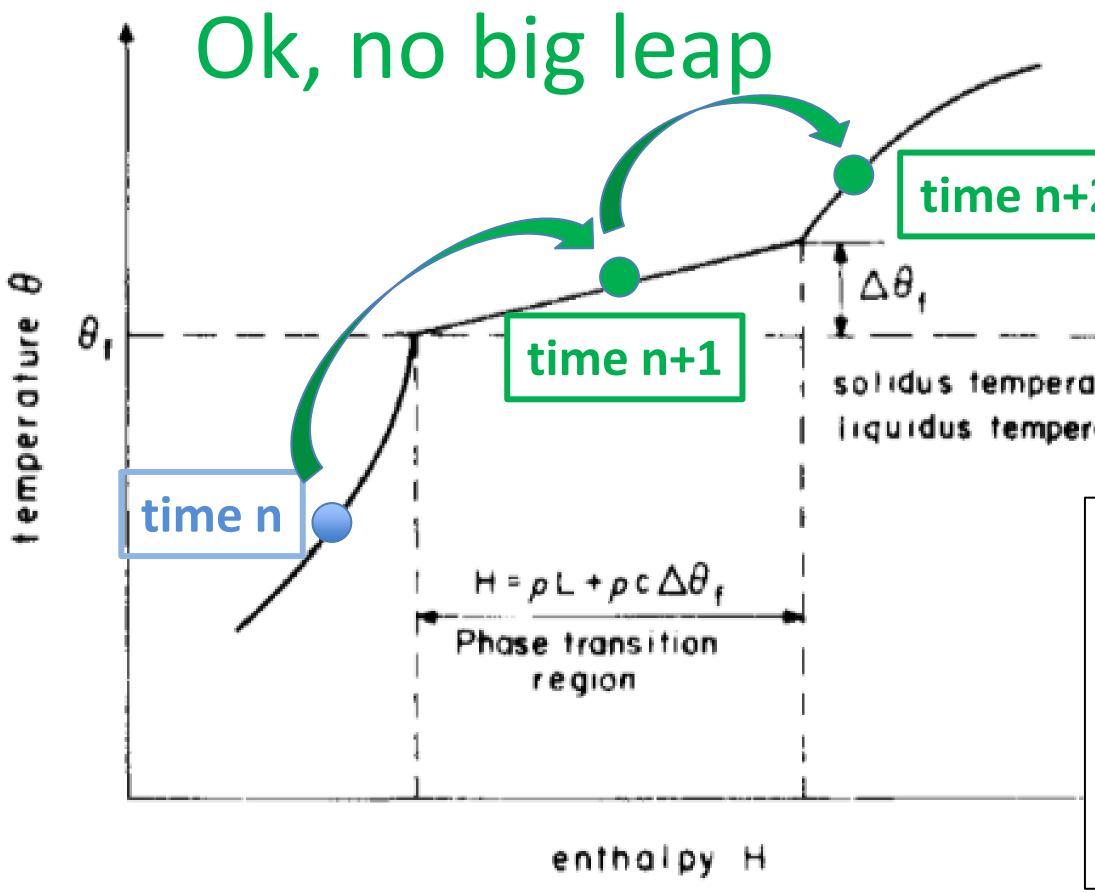
Apparent Heat Capacity: latent heat peak skipping

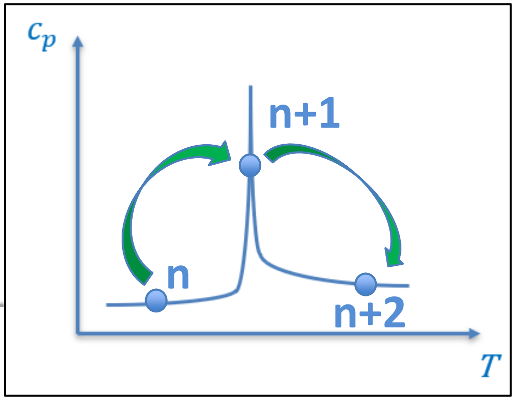




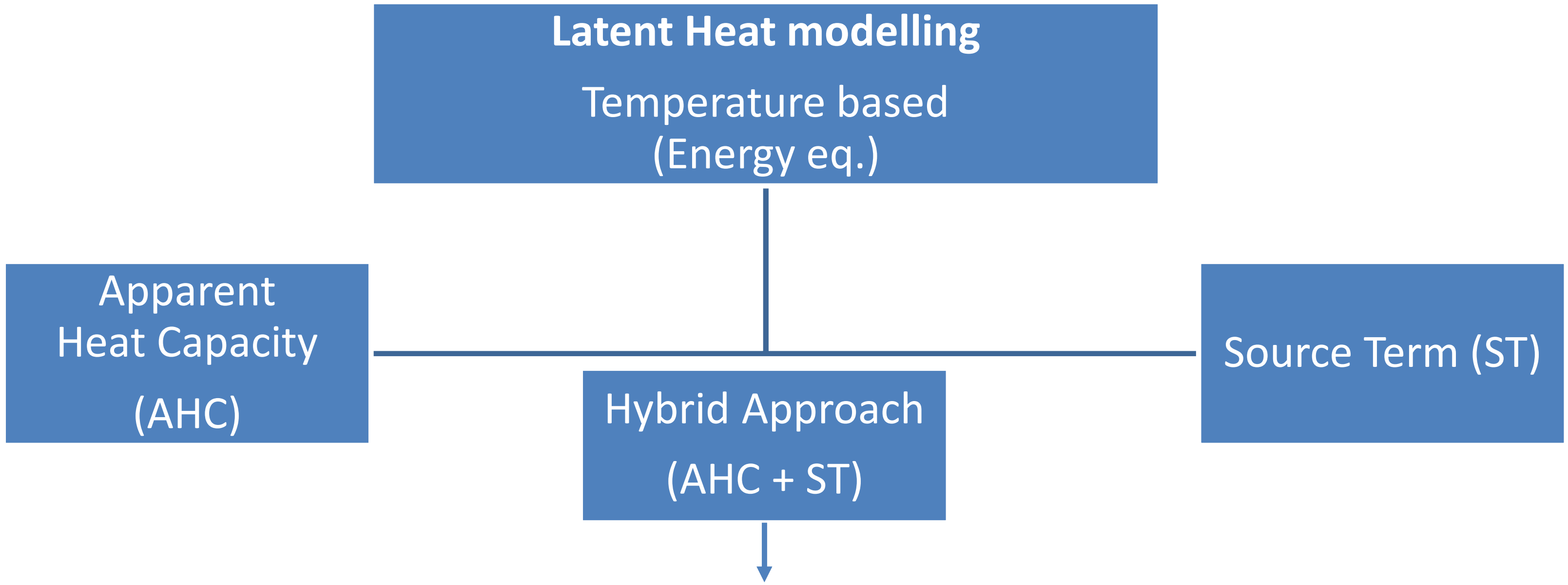
Numerical Modelling

Apparent Heat Capacity: latent heat peak skipping





Numerical Modelling

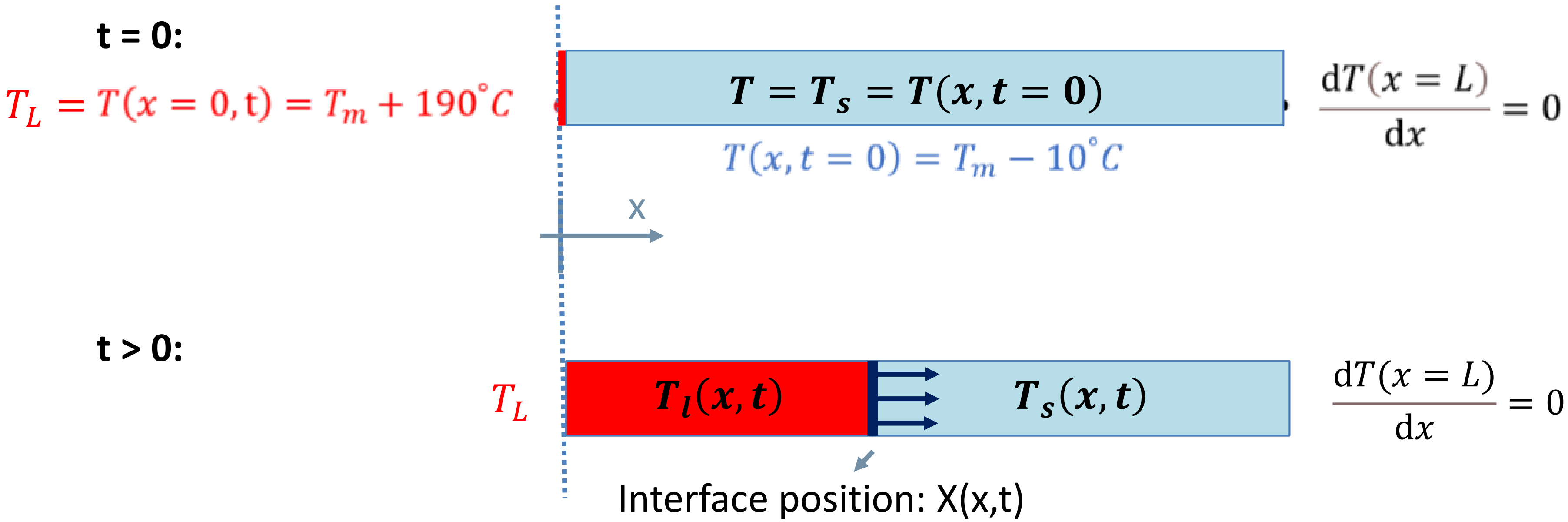


AHC + ST approach:

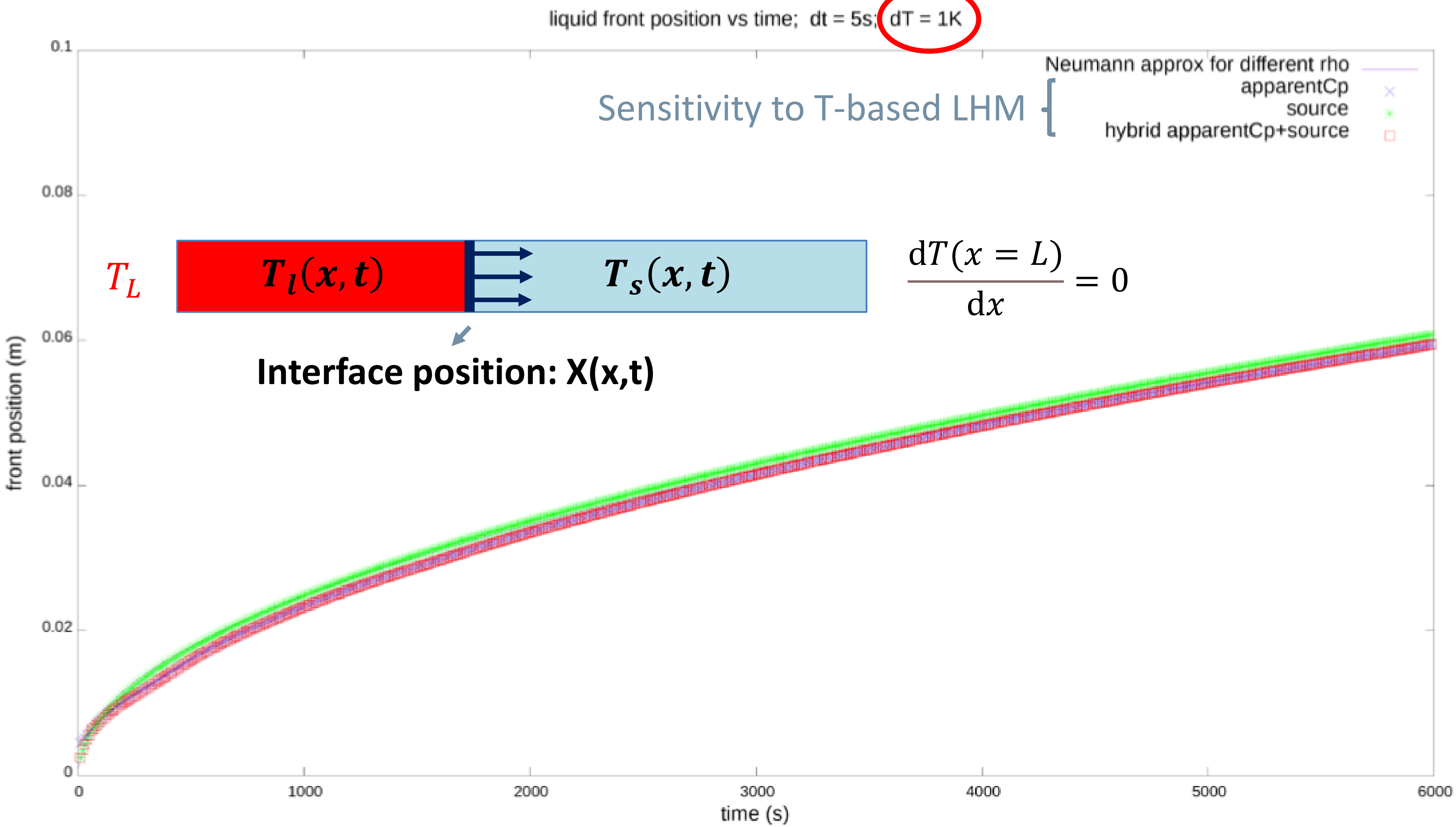
- Start with AHC scheme
- Check for the leap
- If leap occurs, use iterative ST scheme for this timestep

Verification – Conduction

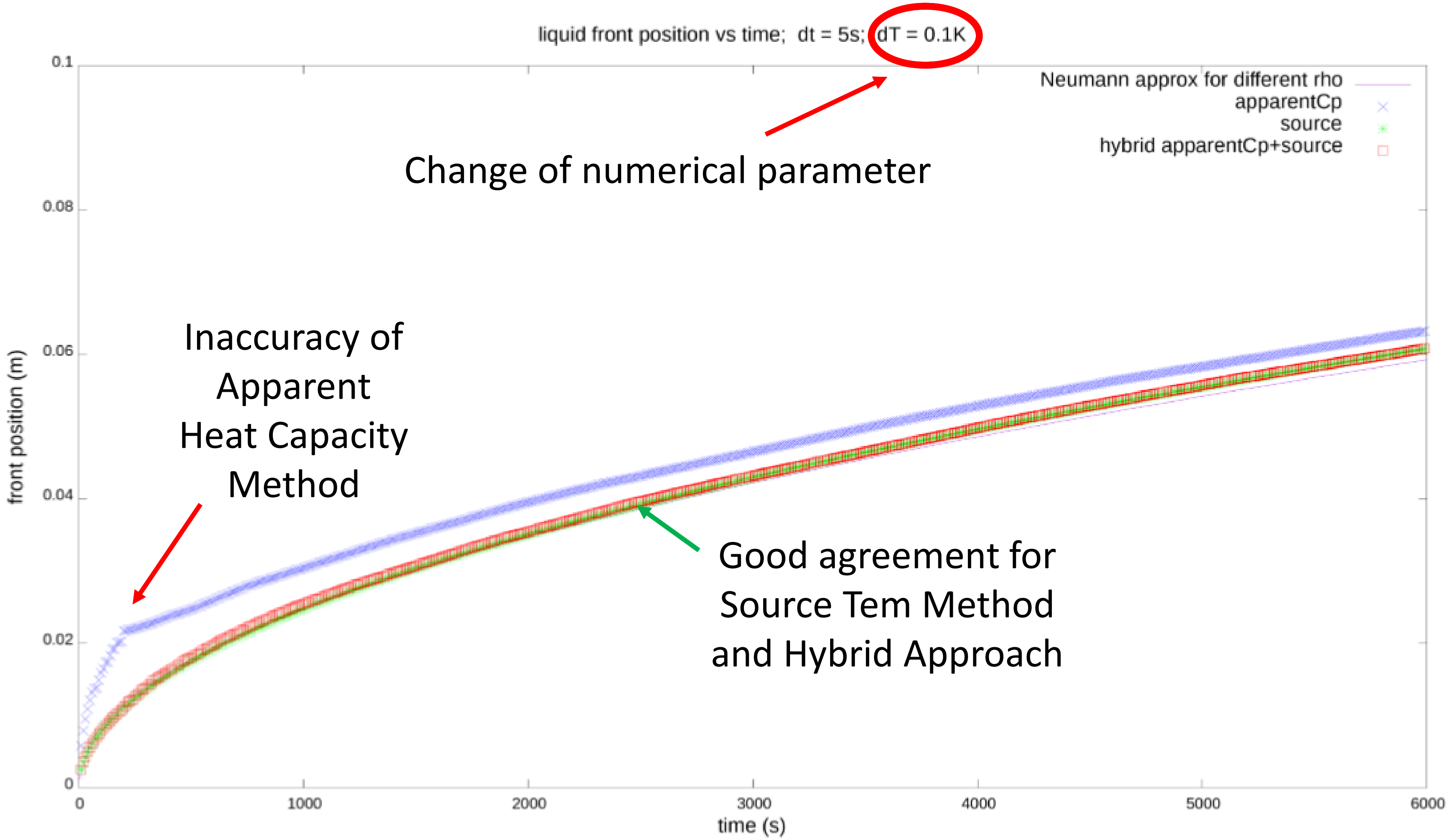
- 1D case: finite slab, $0 \leq x \leq L$
- Material properties: LiF_4
- Melting problem: initially solid, melts from left to right
- Check against analytical solution of the Stefan Problem



Verification - Conduction

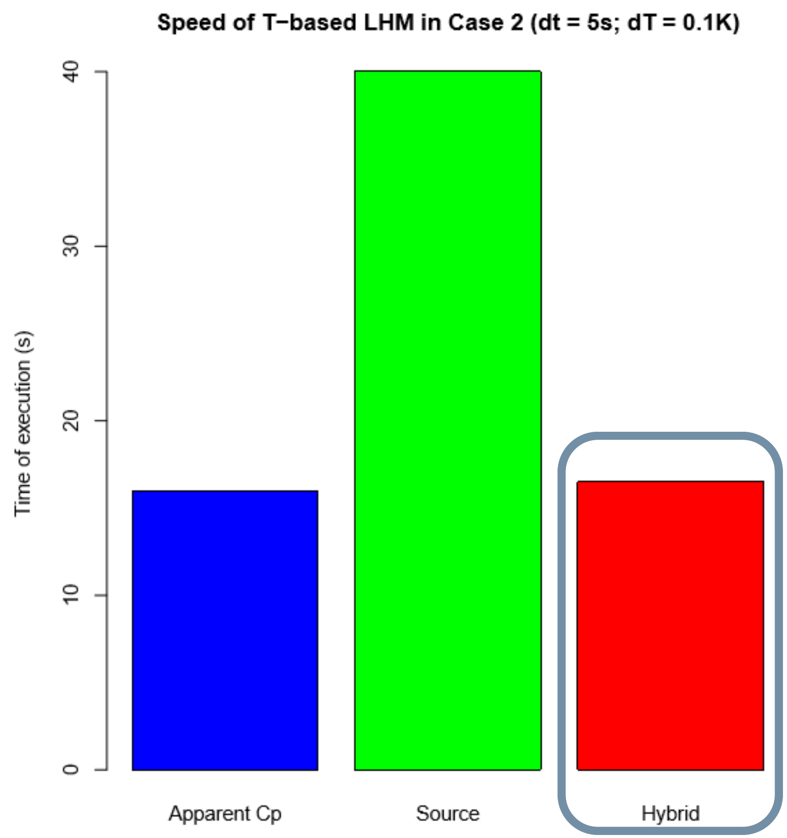


Verification - Conduction



Verification - Conduction

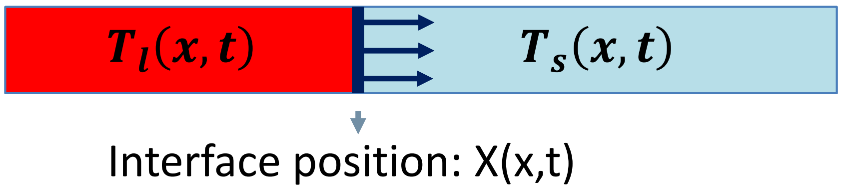
Run time of the case using different Latent Heat Models

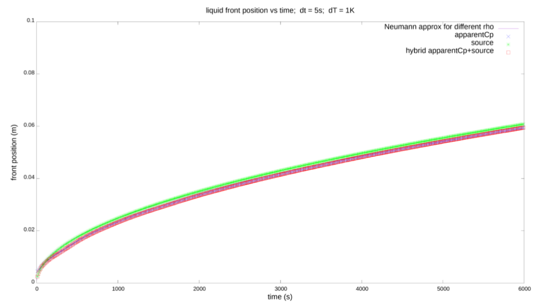


- ✓ Reduced computational cost of the hybrid approach
- ✓ Reduced sensitivity to the choice of the numerical parameters

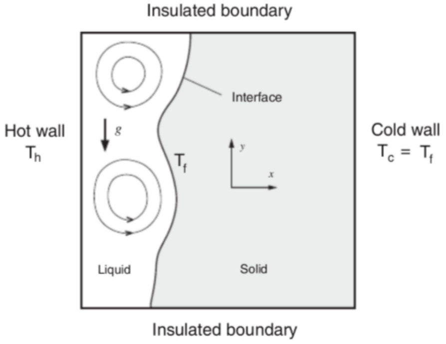
Verification

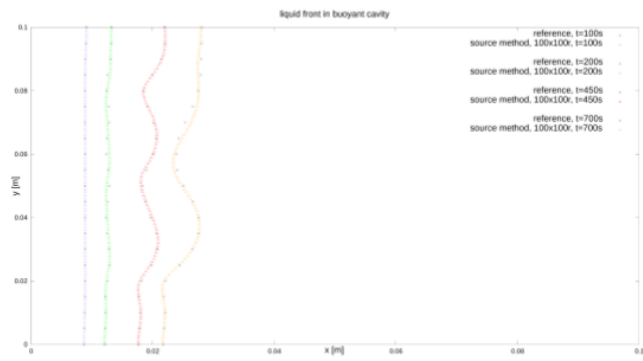
Pure Conduction ⟷ Analytical Solution





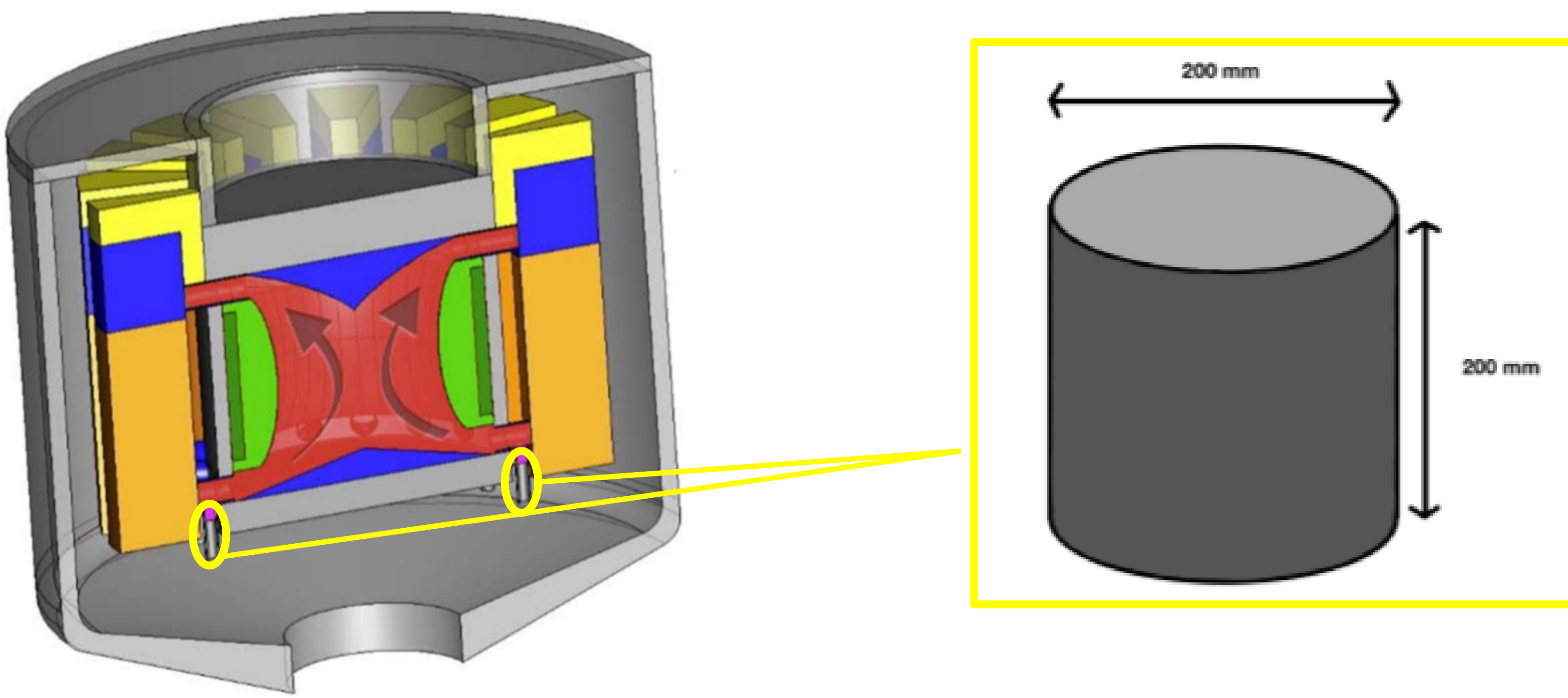
Convection ⟷ Numerical Benchmark





Application to Freeze Valve

What can be simulated?



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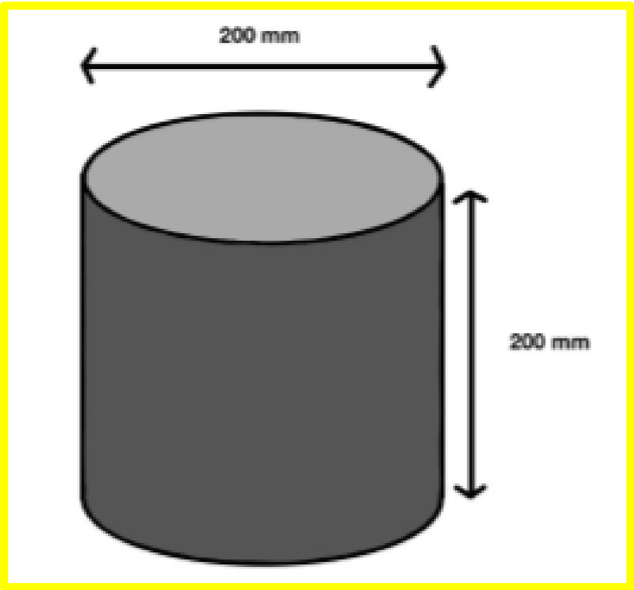
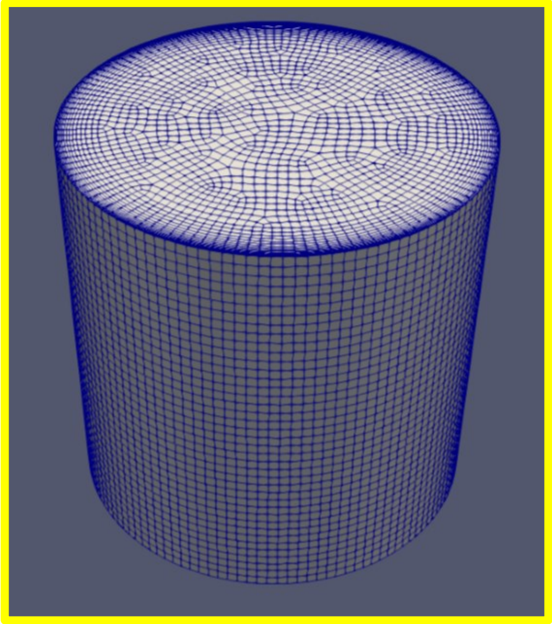
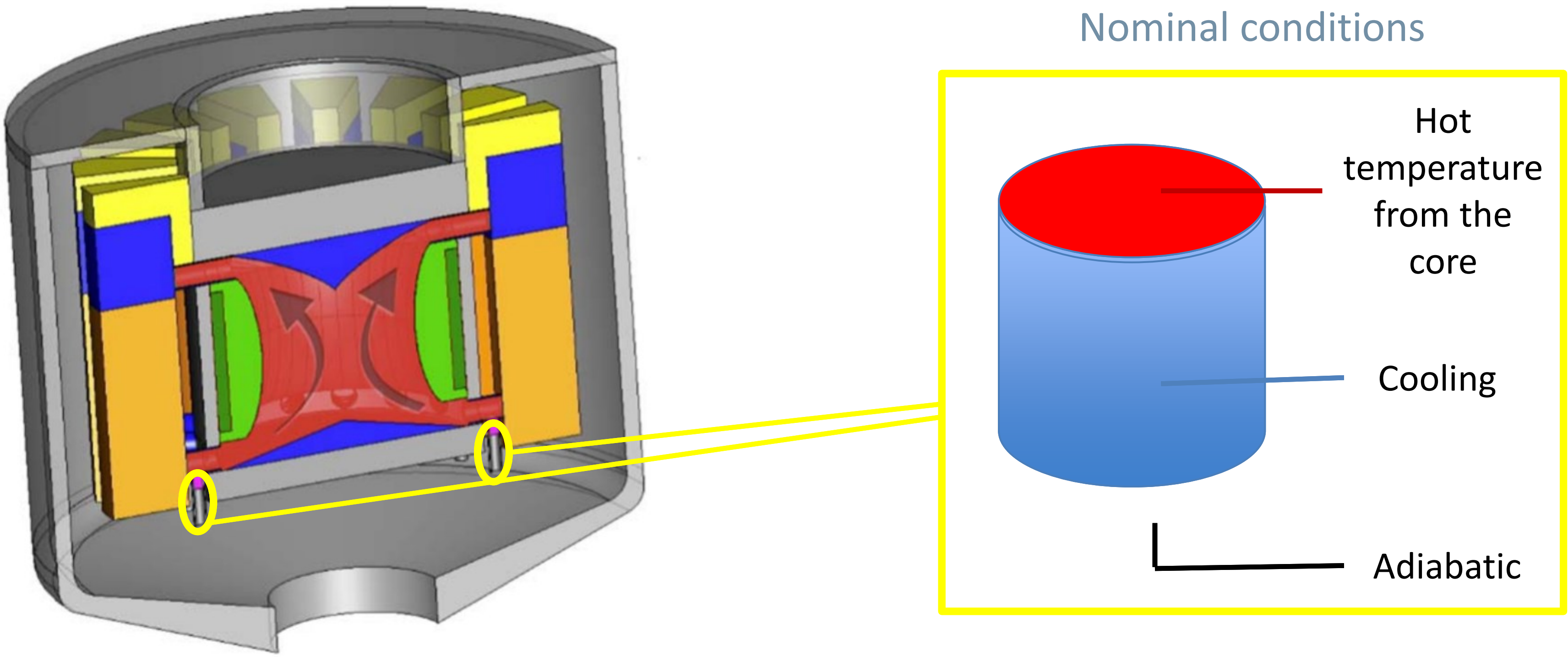




Application to Freeze Valve

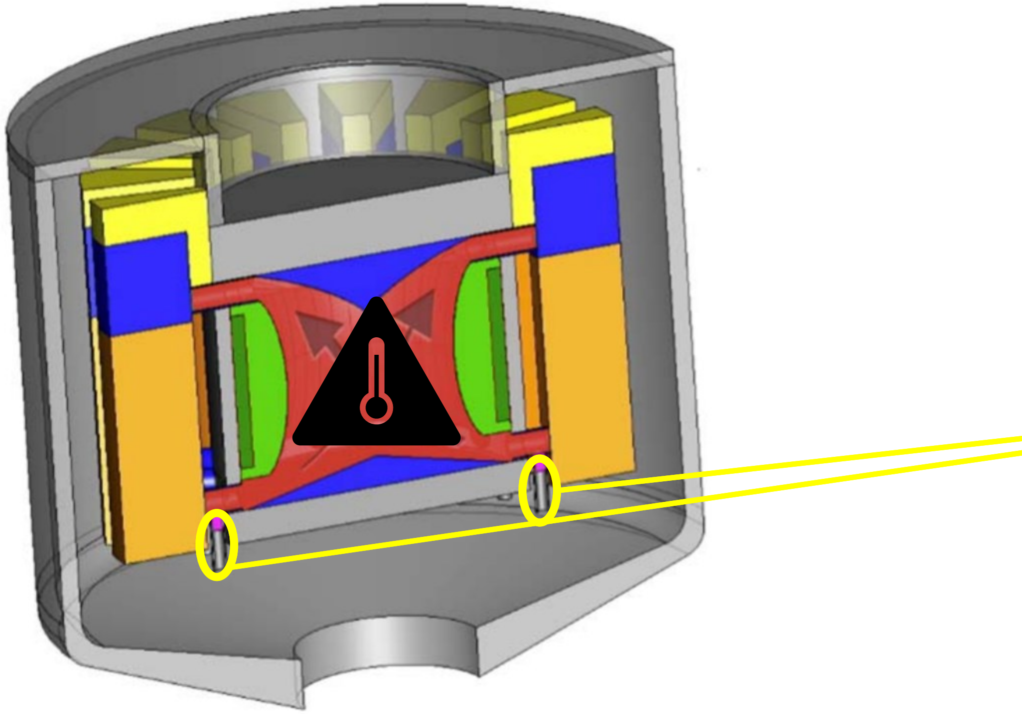
What can be simulated?

Nominal conditions

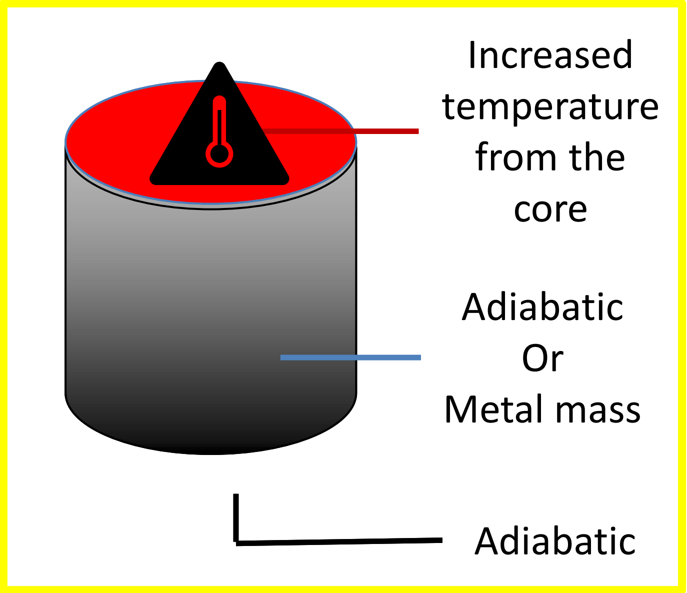


Application to Freeze Valve

What can be simulated?

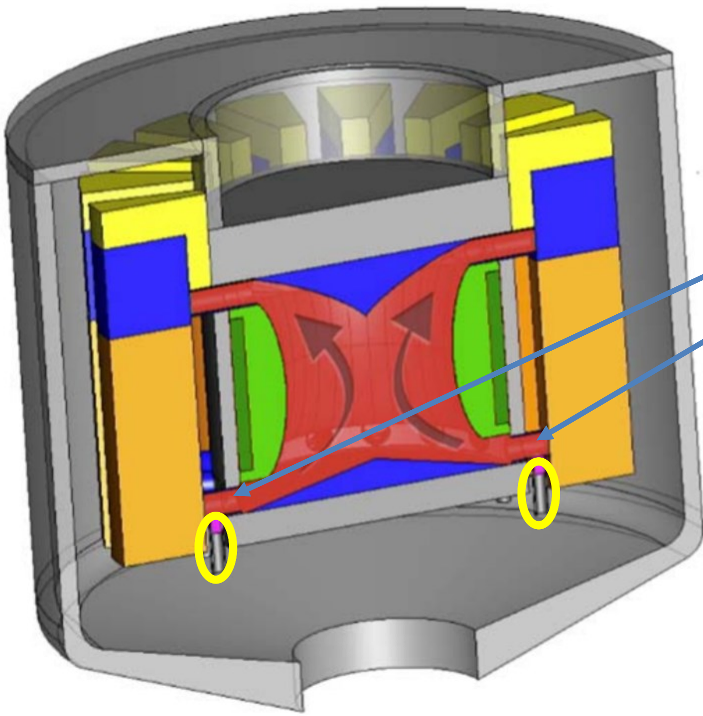


Melting Transient



Application to Freeze Valve

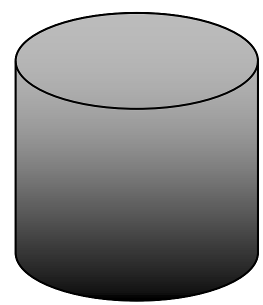
What can be simulated?

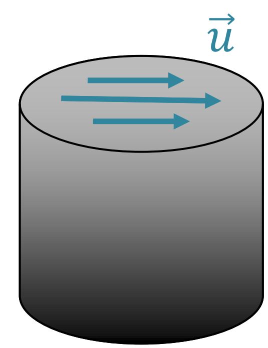


Moving Fluid Above the Valve?

no → Pure Heat Conduction

yes → Convection

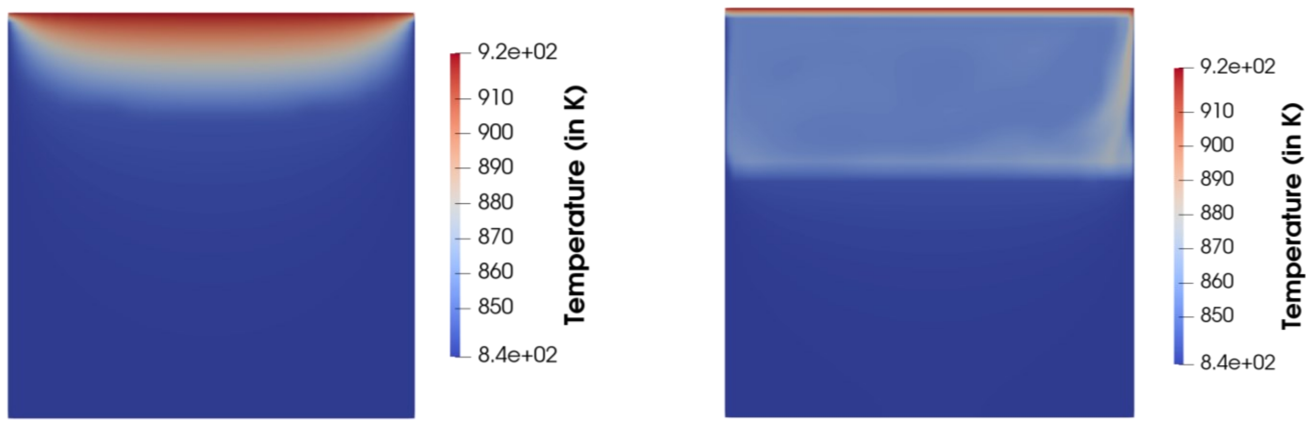




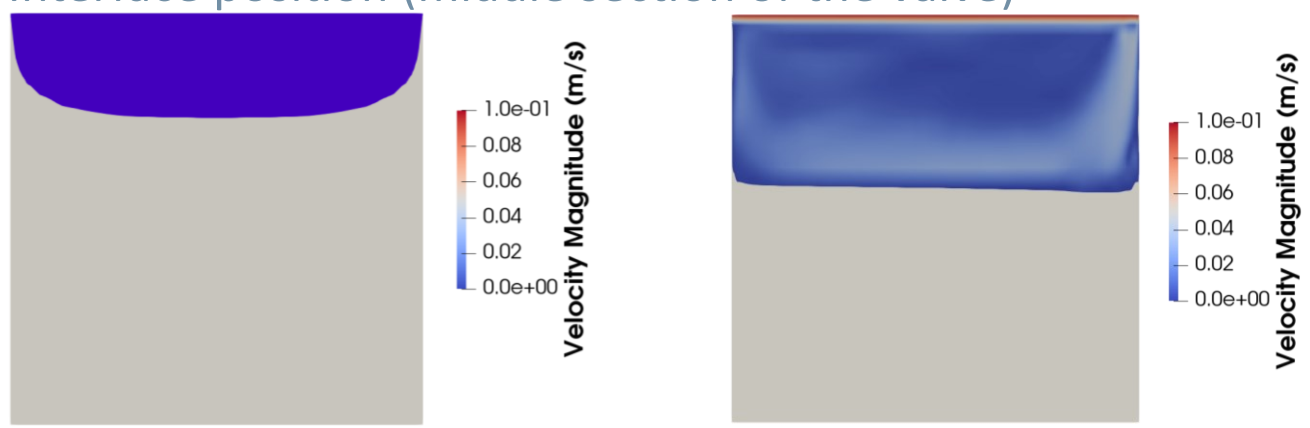
Application to Freeze Valve

Steady state: Effects of convection

Temperature Field (middle section of the valve)



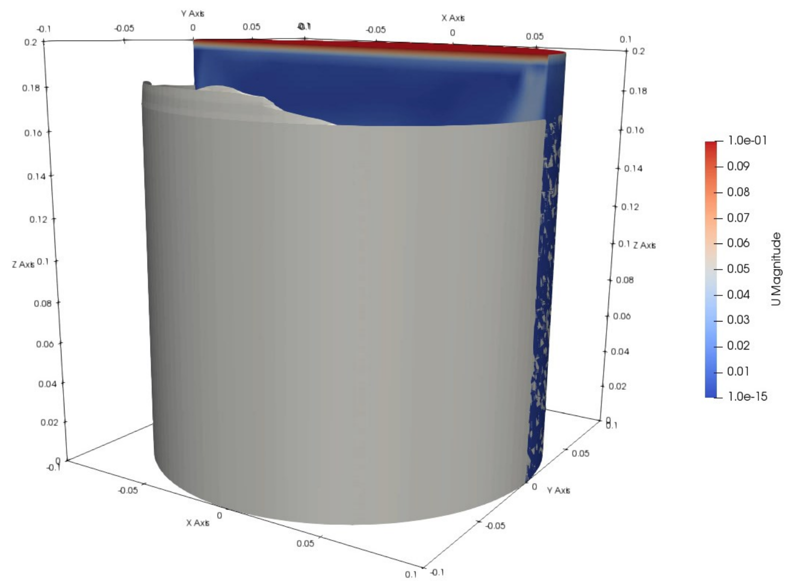
Interface position (middle section of the valve)



Conclusions & Future work

Solver capabilities

- ✓ Efficiently **solve** single-region heat transfer problems with **melting** and solidification
- ✓ Able to handle **complex bc**
- ✓ Able to take into account **thermophysical properties** of salt



Future work

- ✓ **Multi-region** solver for quantitative analysis
- ✓ Merging with existing **multi-physics** solver
- ✓ Perform **validation**
- ✓ **Propose** a new **detailed design** based on quantitative analysis