teknova

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A Model for High Temperature Inductive Heating

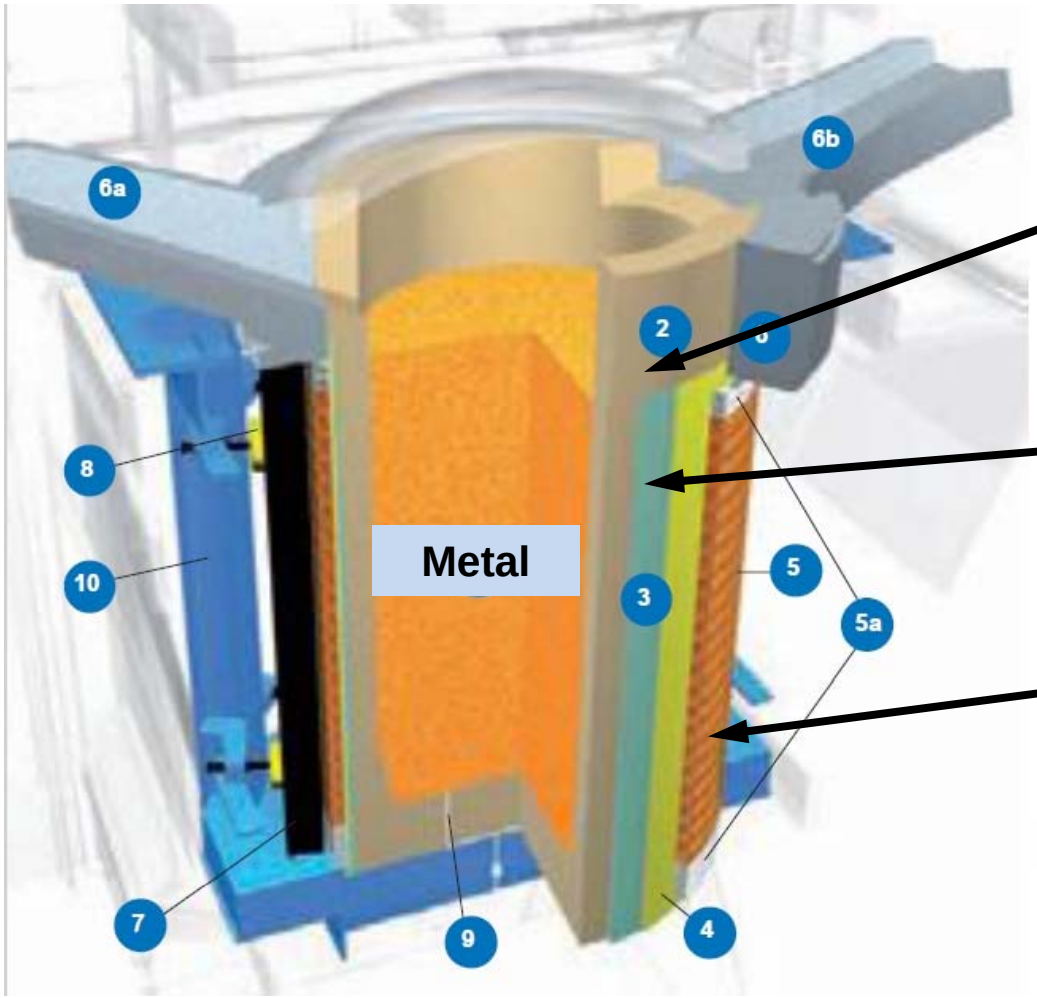
2009 COMSOL Conference

Milano

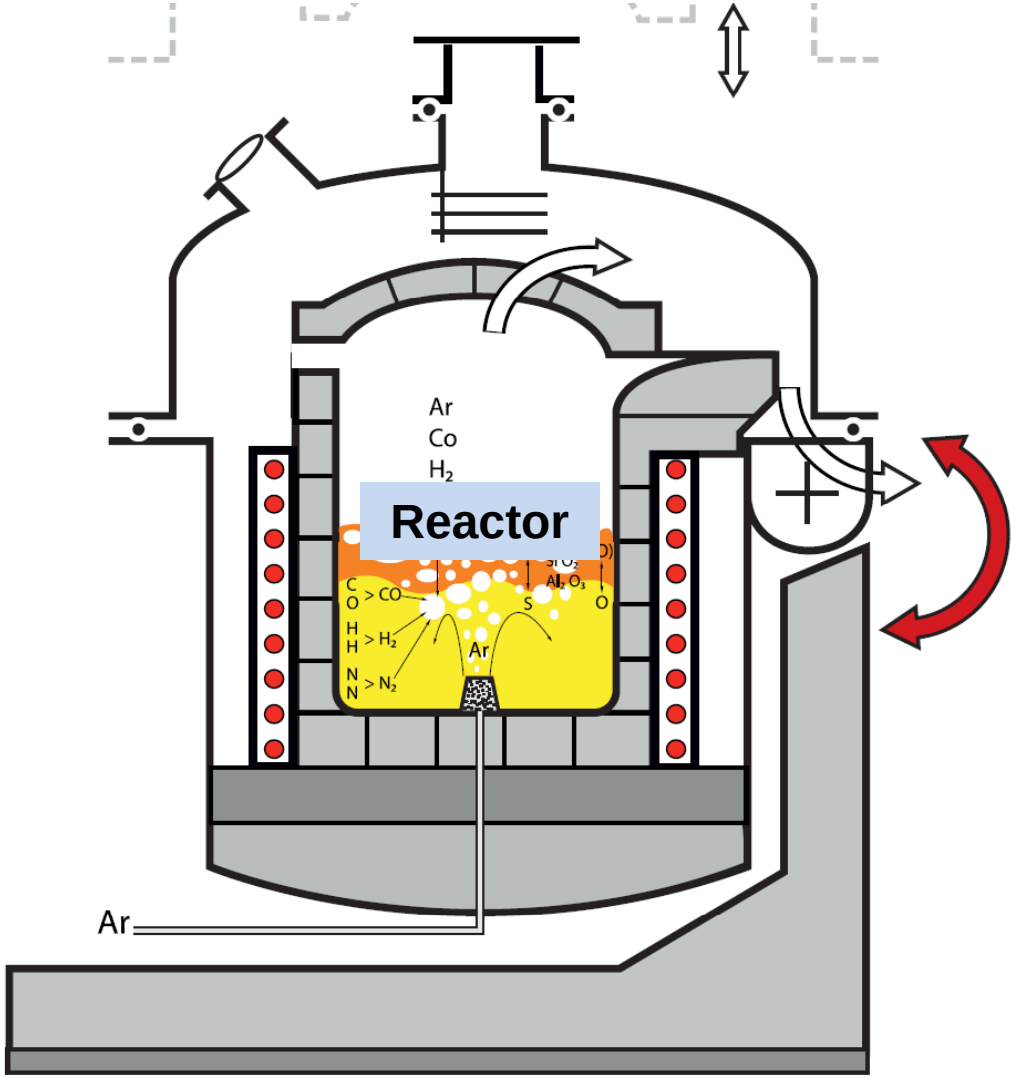
Two Issues

- Model
  - Description
  - Some results
- Numerical problems
  - Non-linear model
  - Convergence for time integration

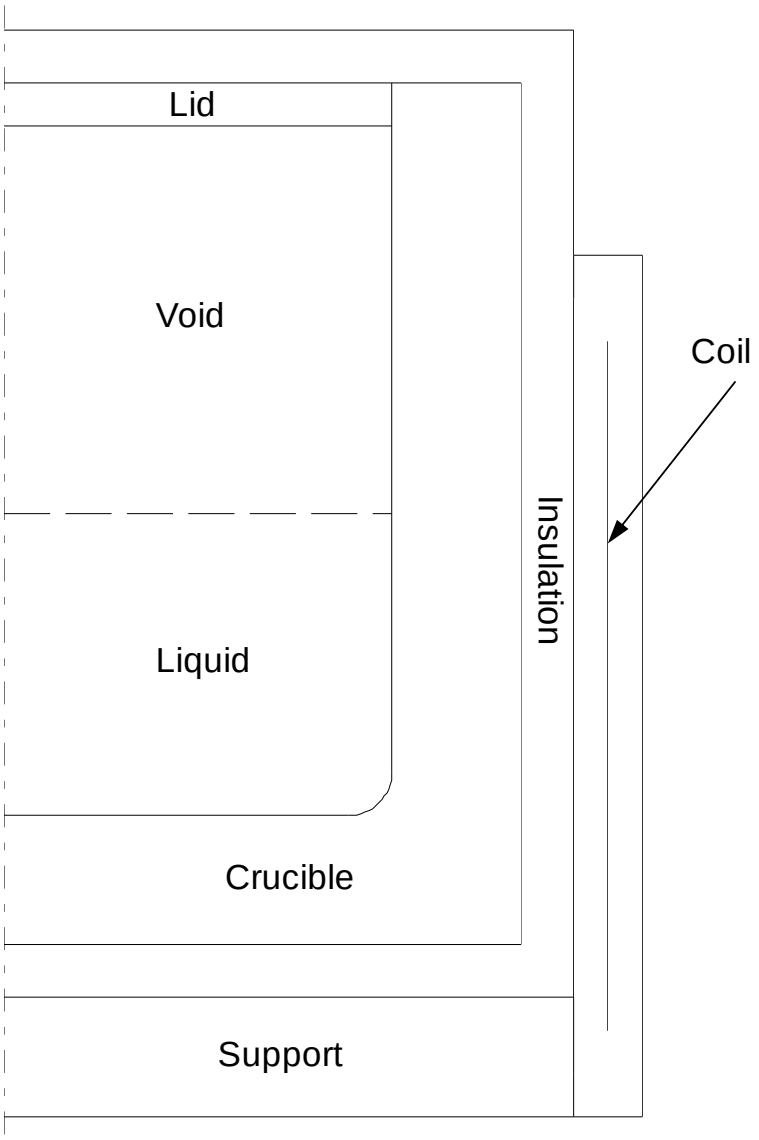
Example – Industrial Furnace Otto Junker



Example – ALD furnace

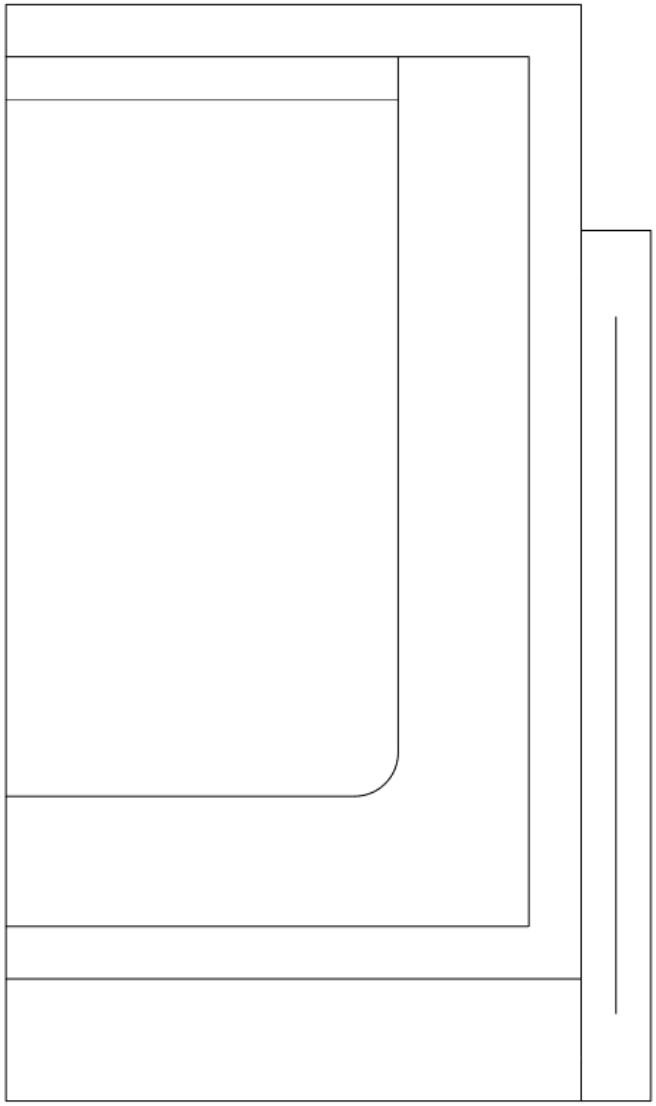


High Temp Inductive Heating Axially Symmetric Model



Special:
- Non-conductive liquid
- **Crucible** heated by induction

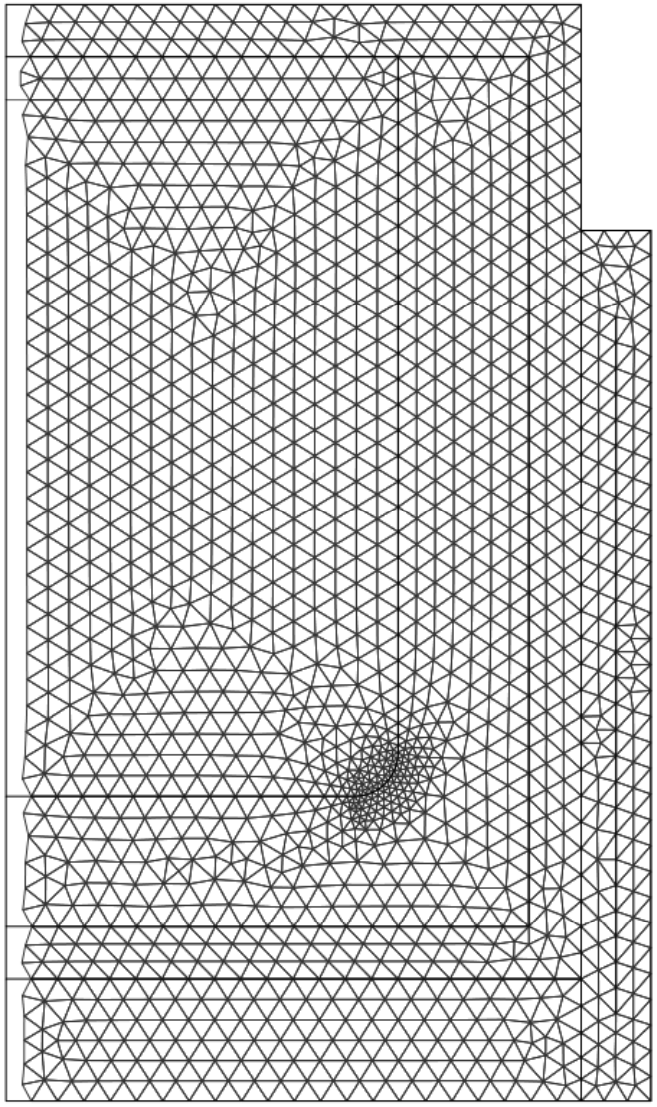
Multiphysics – DAEs and Three Application Modes



- Axial Symmetry

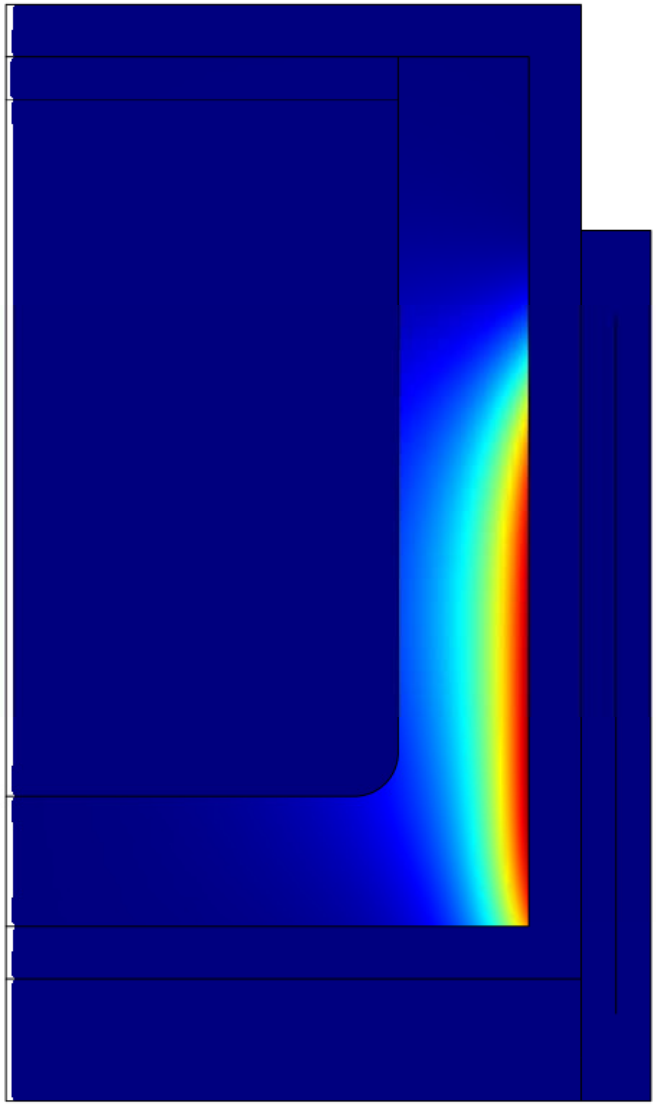
- AC Power Electromagnetics
- Heat Transfer by Conduction
- Stress-Strain
- Discrete State Variables, DAEs

Multiphysics Element Grid



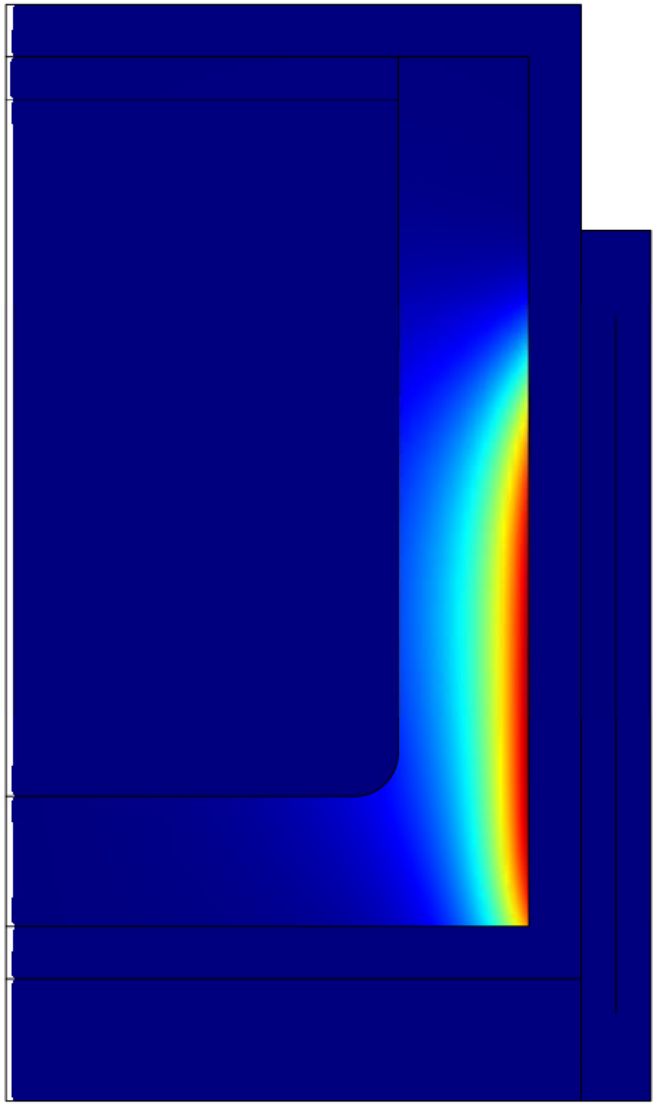
- Element mesh for the simulations

Multiphysics
AC Power Electromagnetics



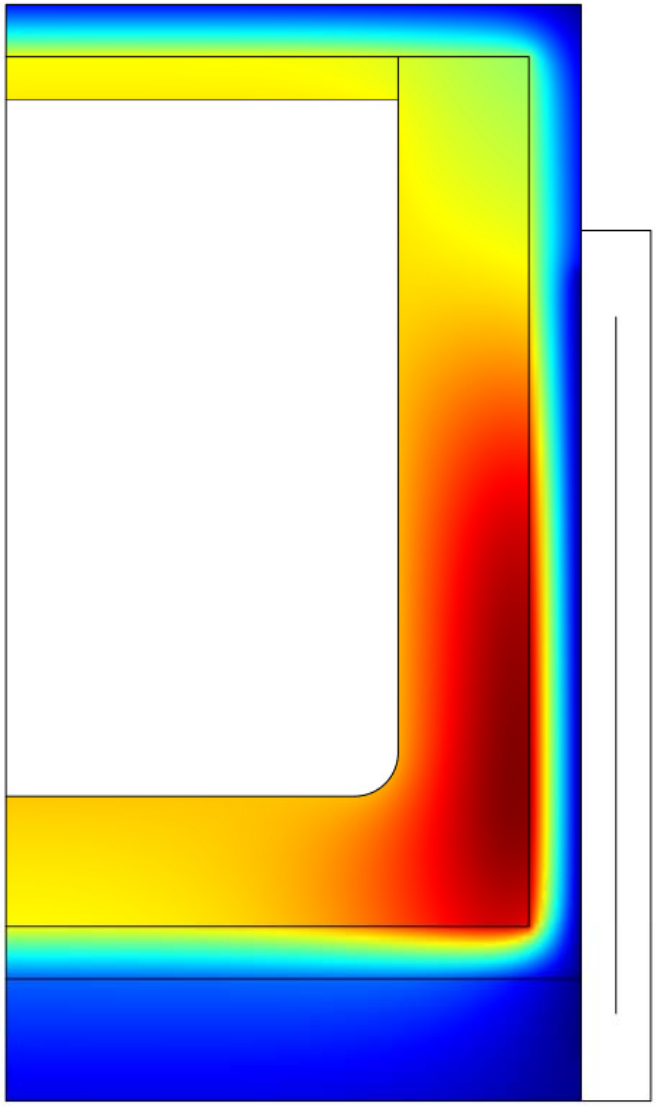
- Power distribution
  - Input to heat equation

Multiphysics
AC Power Electromagnetics



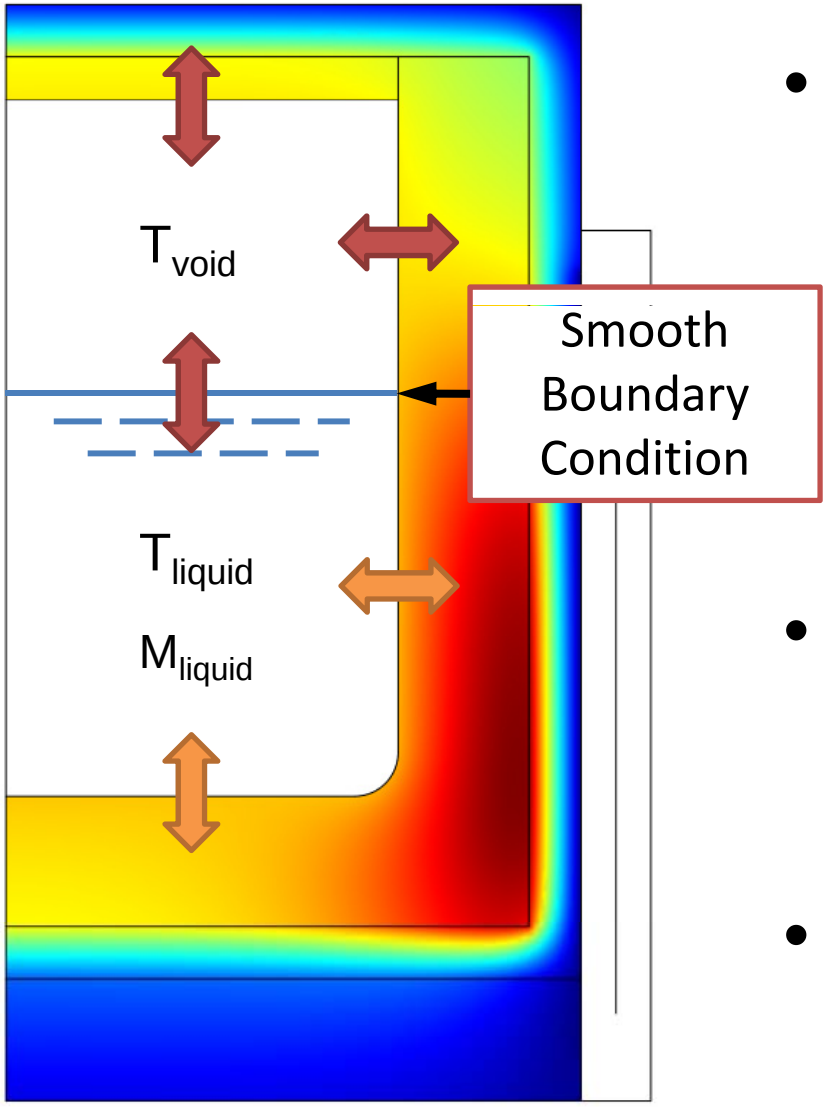
- Power distribution
  - Input to heat equation
- Linear equations
  - Arbitrary coil current
  - Compute **power distribution**
  - Integrate to find total power
  - Scale to **known** total power

Multiphysics
Heat Transfer



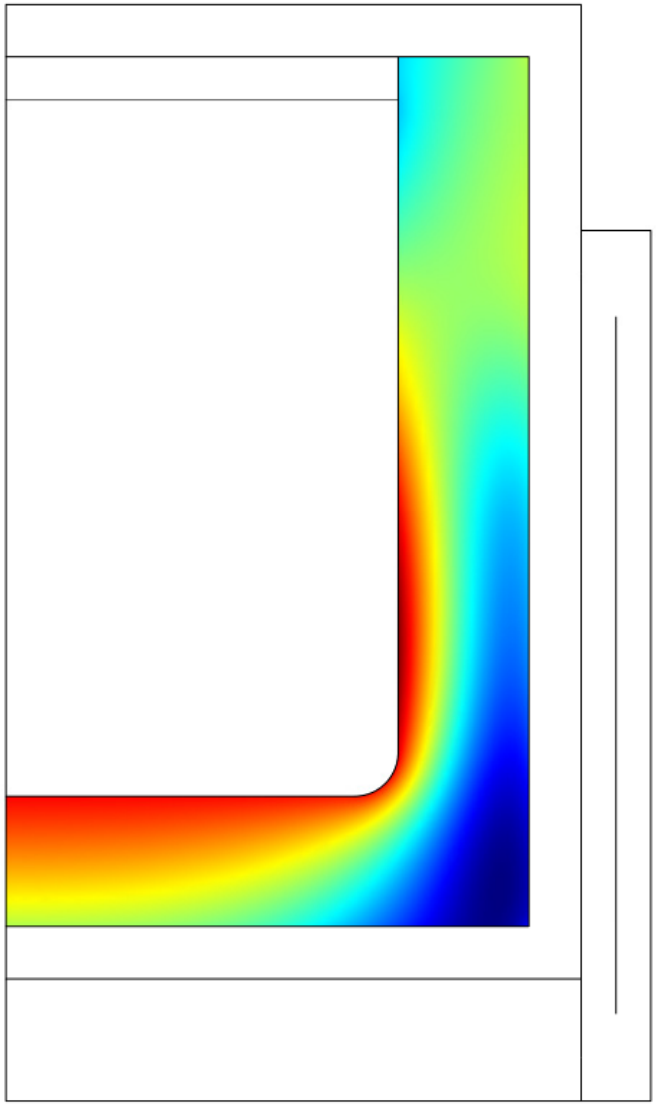
- Crucible, lid, insulation, support
- Outside: Boundary conditions
- Inside: Couple to void and liquid

Multiphysics
Discrete state variables, DAEs



- Heat balance: Void
  - Radiation
- Heat balance: Liquid
  - Convective heat transfer
- Material balance: Liquid
- Can be far more complex

Multiphysics Stress-Strain



- Crucible only
- Insulation is soft

- Example: Stress in the angular direction

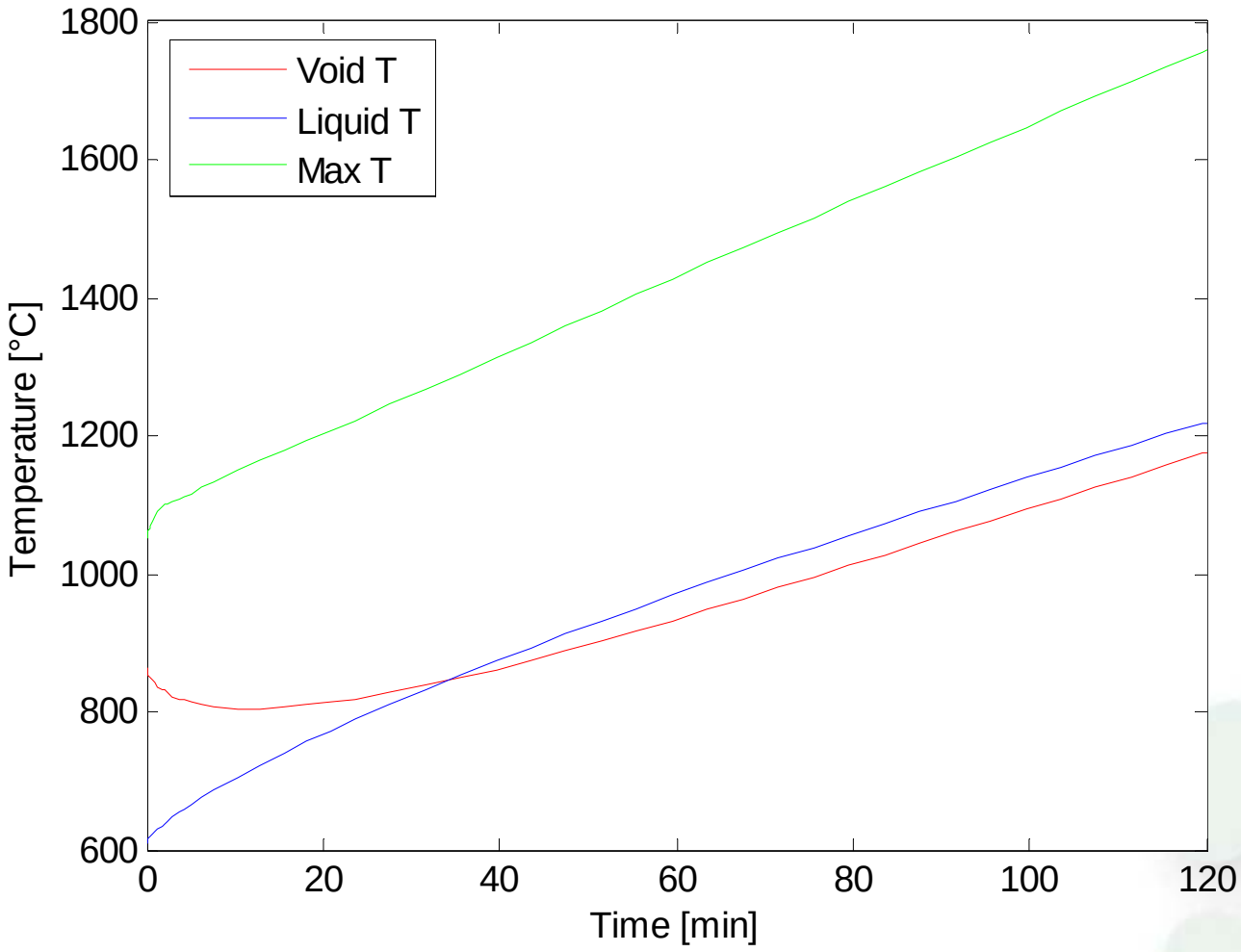
Multiphysics
Non-linear system

- Radiation
- Temperature dependent material data
- Smoothing
- Moving boundary condition

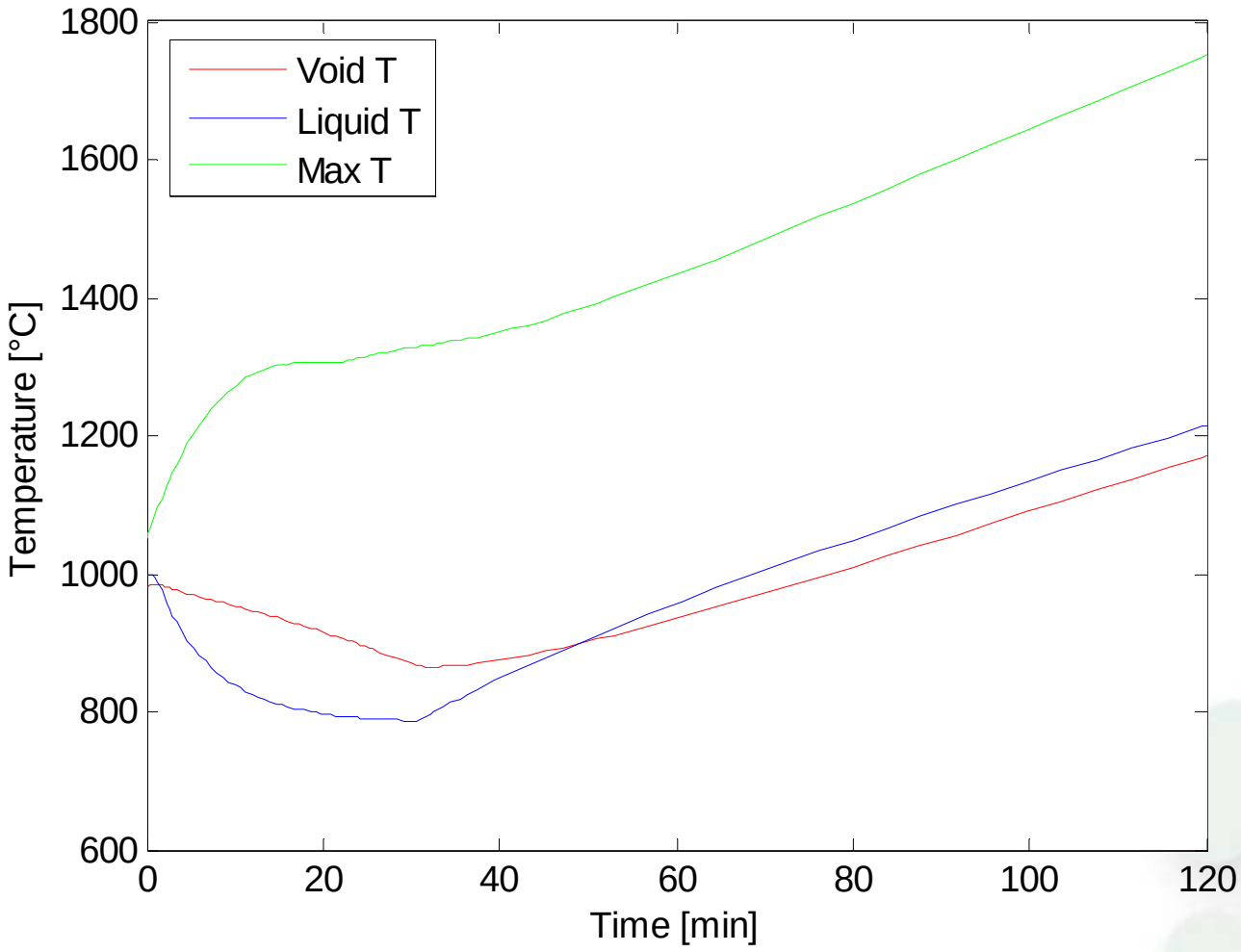
Two Case Studies

- Instantaneous Filling
  - Initially: 400 kg liquid at 1000 °C
  - Add 800 kg liquid at 400 °C, **instantaneously**
    New state: 1200 kg liquid, 600 °C
  - Simulate 2 hours
- Gradual Filling
  - Initially: 400 kg liquid at 1000 °C
  - Add 800 kg liquid at 400 °C **during ½ hour**
  - Simulate 2 hours (totally)

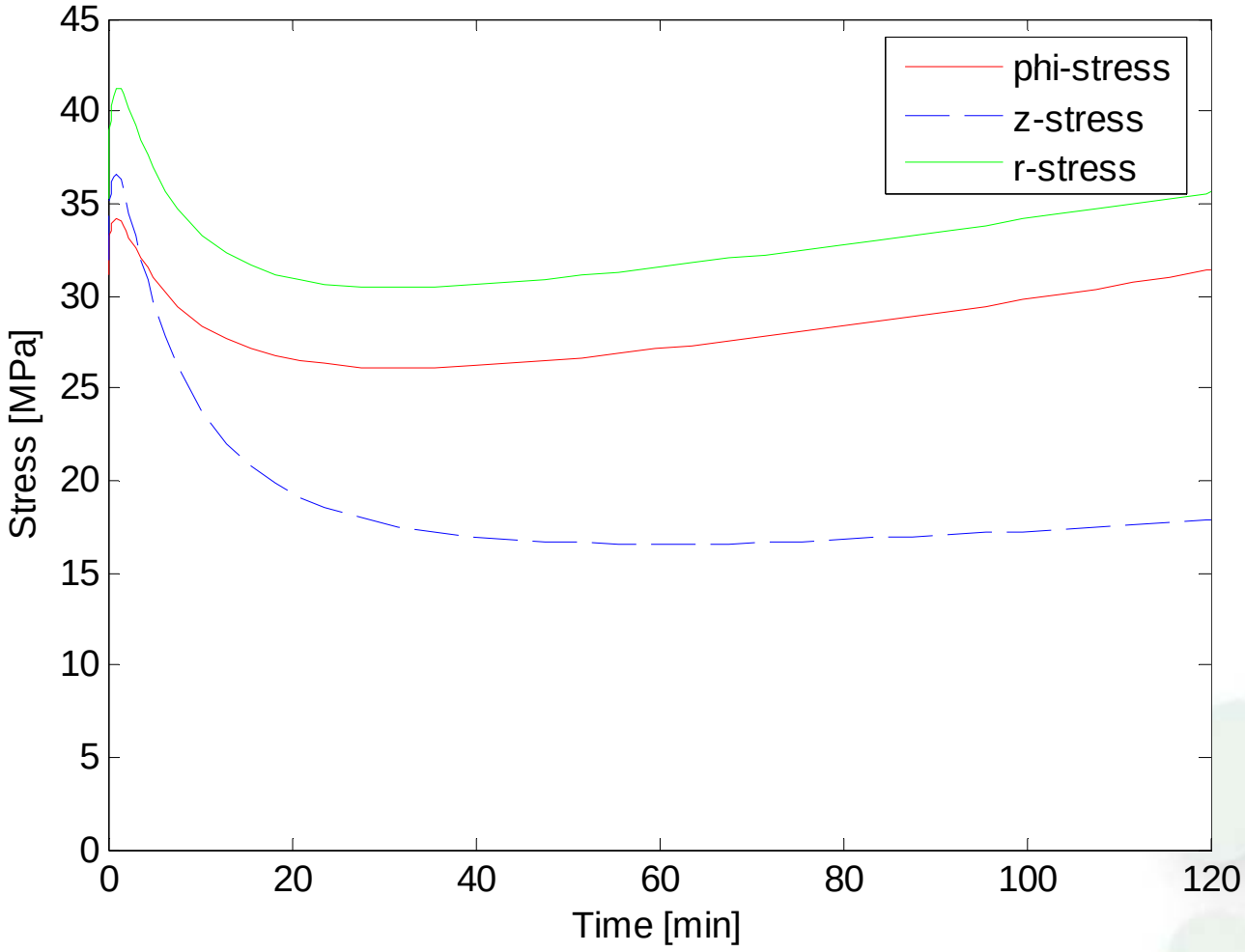
Instantaneous Filling
Main Temperatures



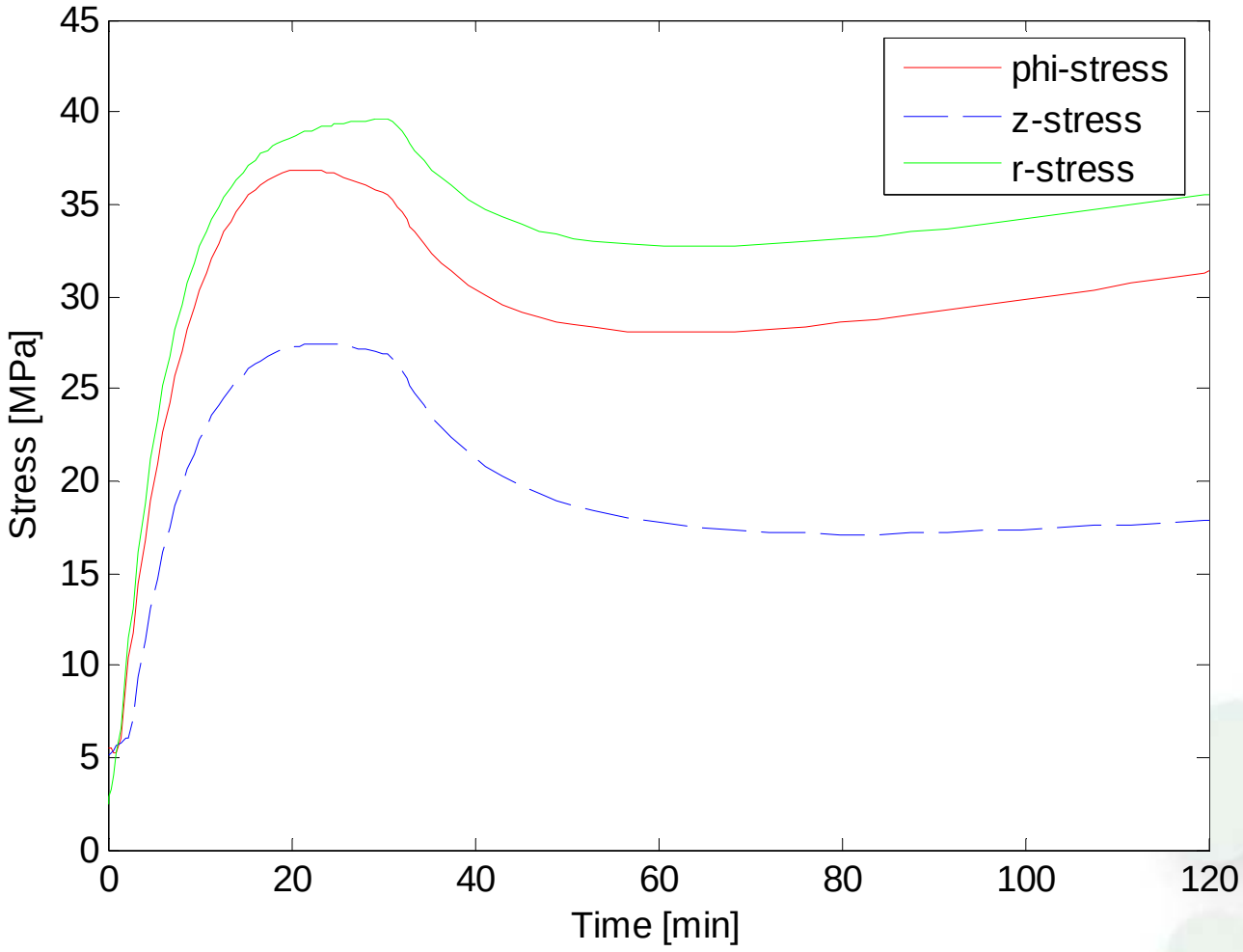
Gradual Filling
Main Temperatures



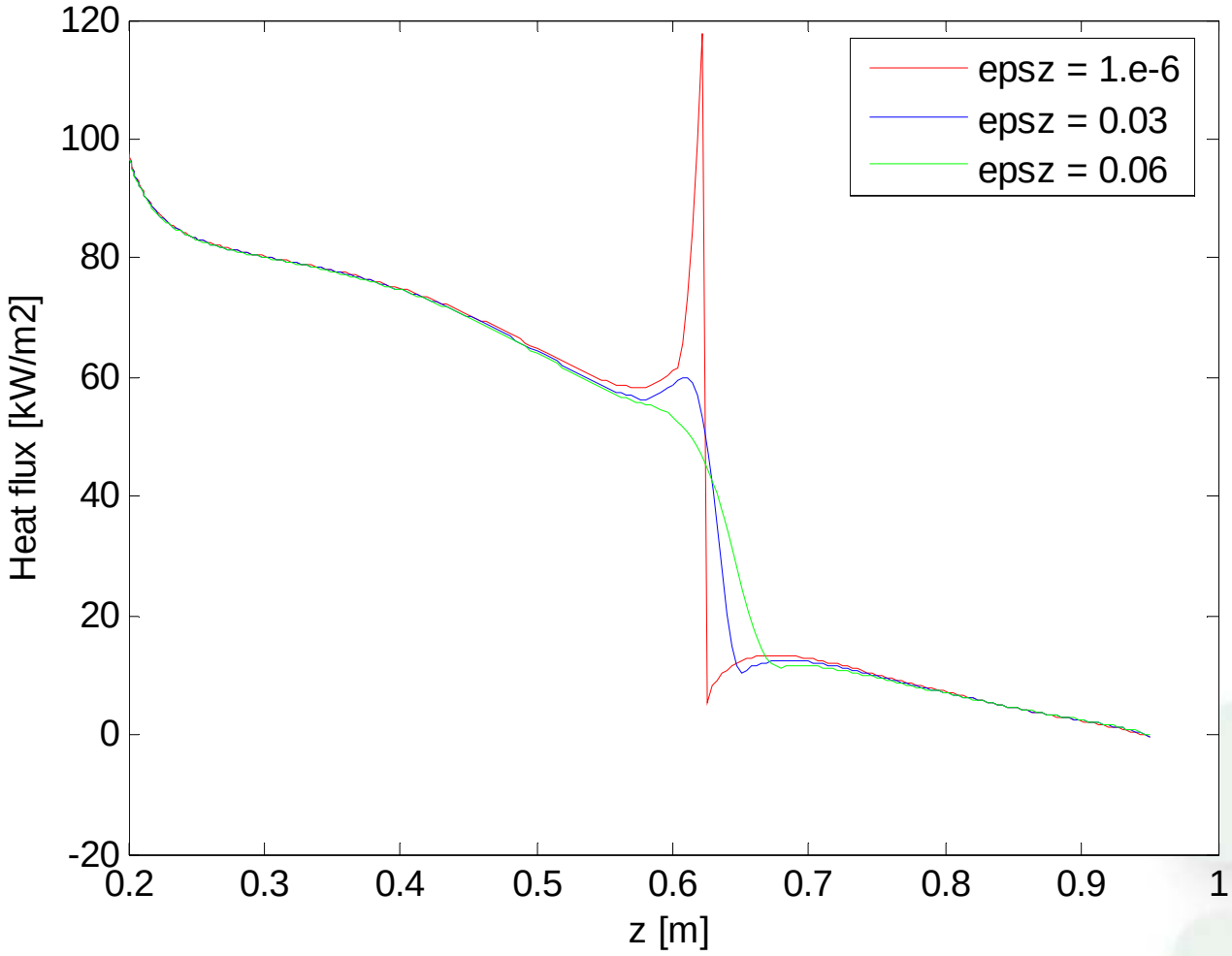
Instantaneous Filling Maximum Stresses



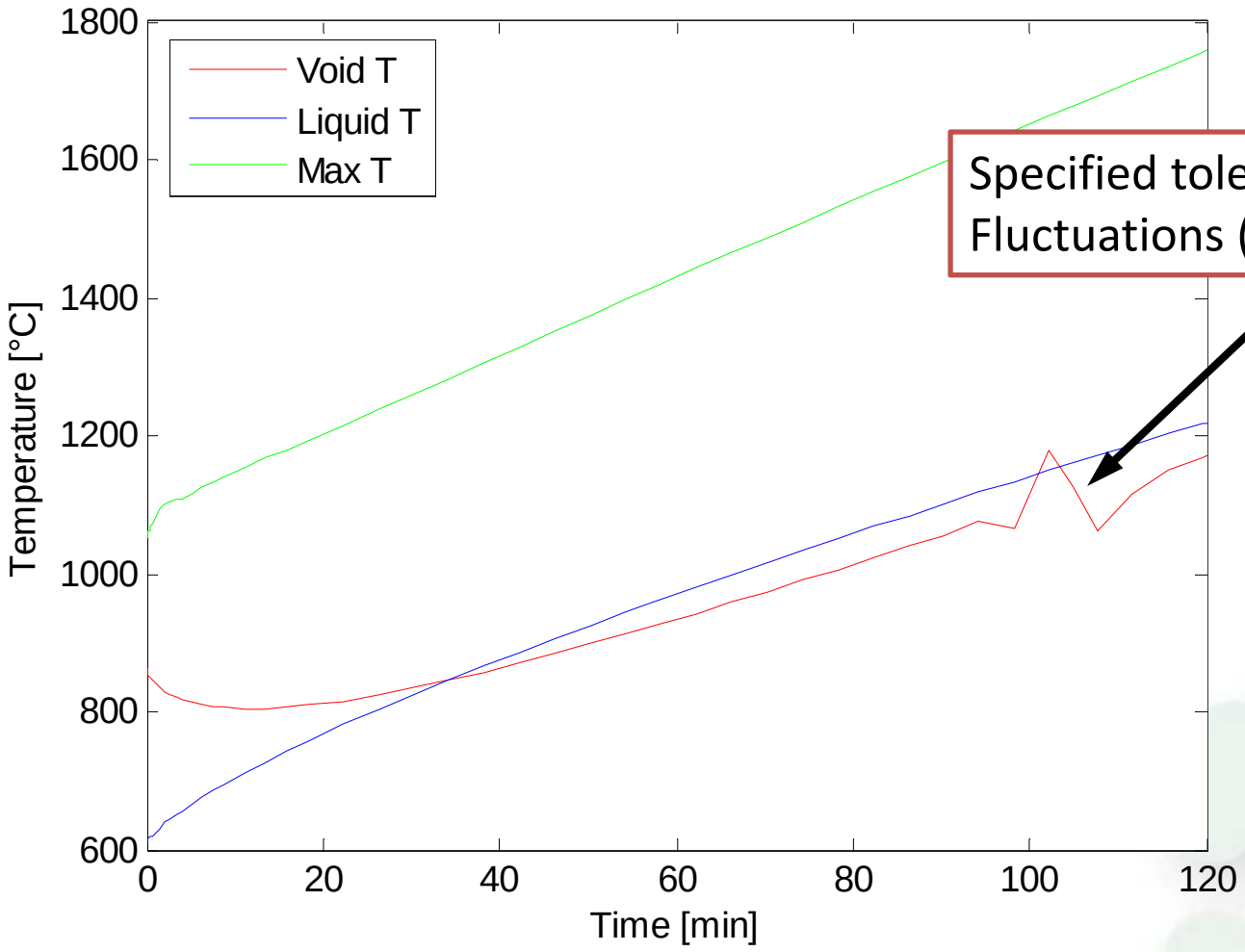
Gradual Filling
Maximum Stresses



Instantaneous Filling Smoothing – Liquid/void interface

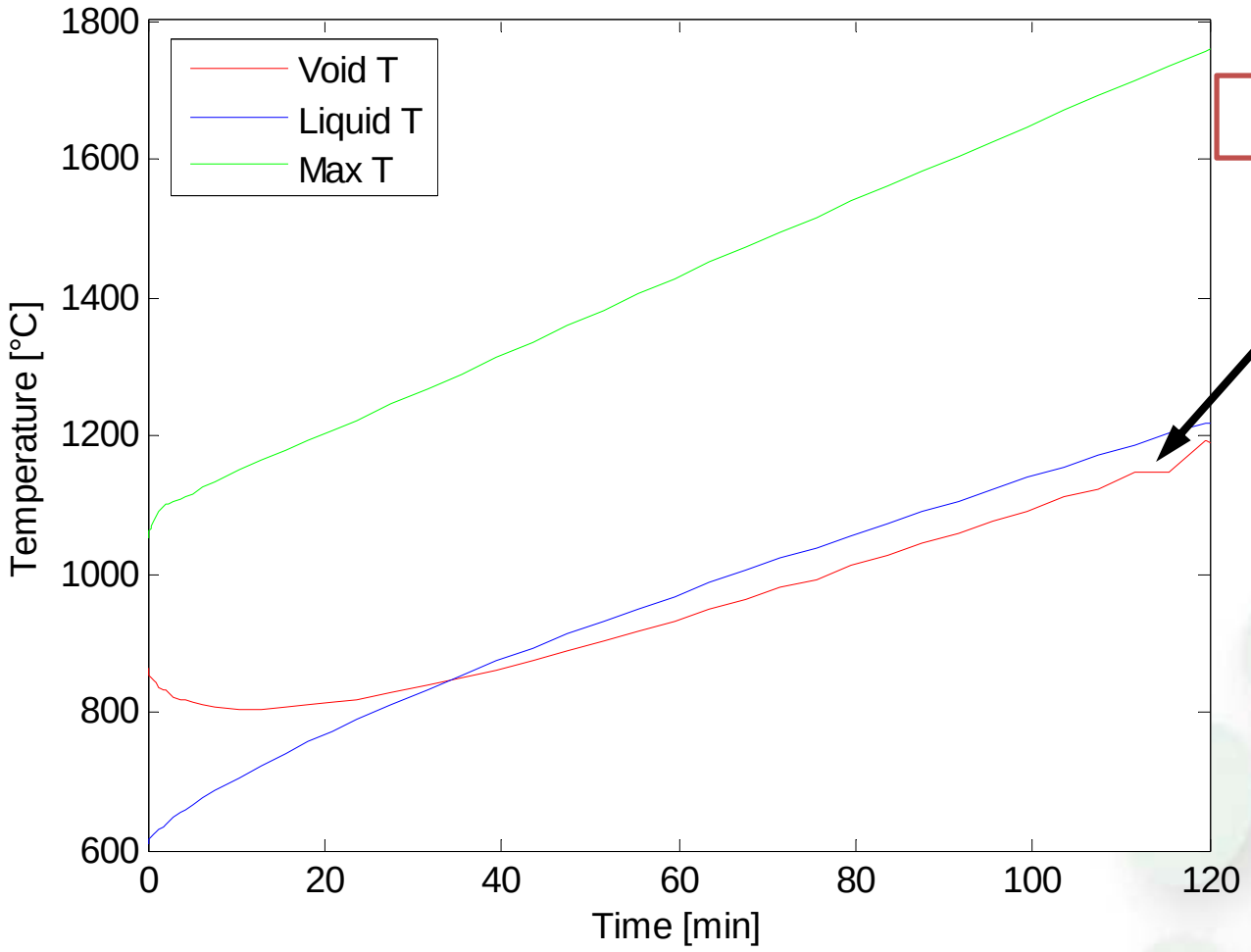


Instantaneous Filling
First run



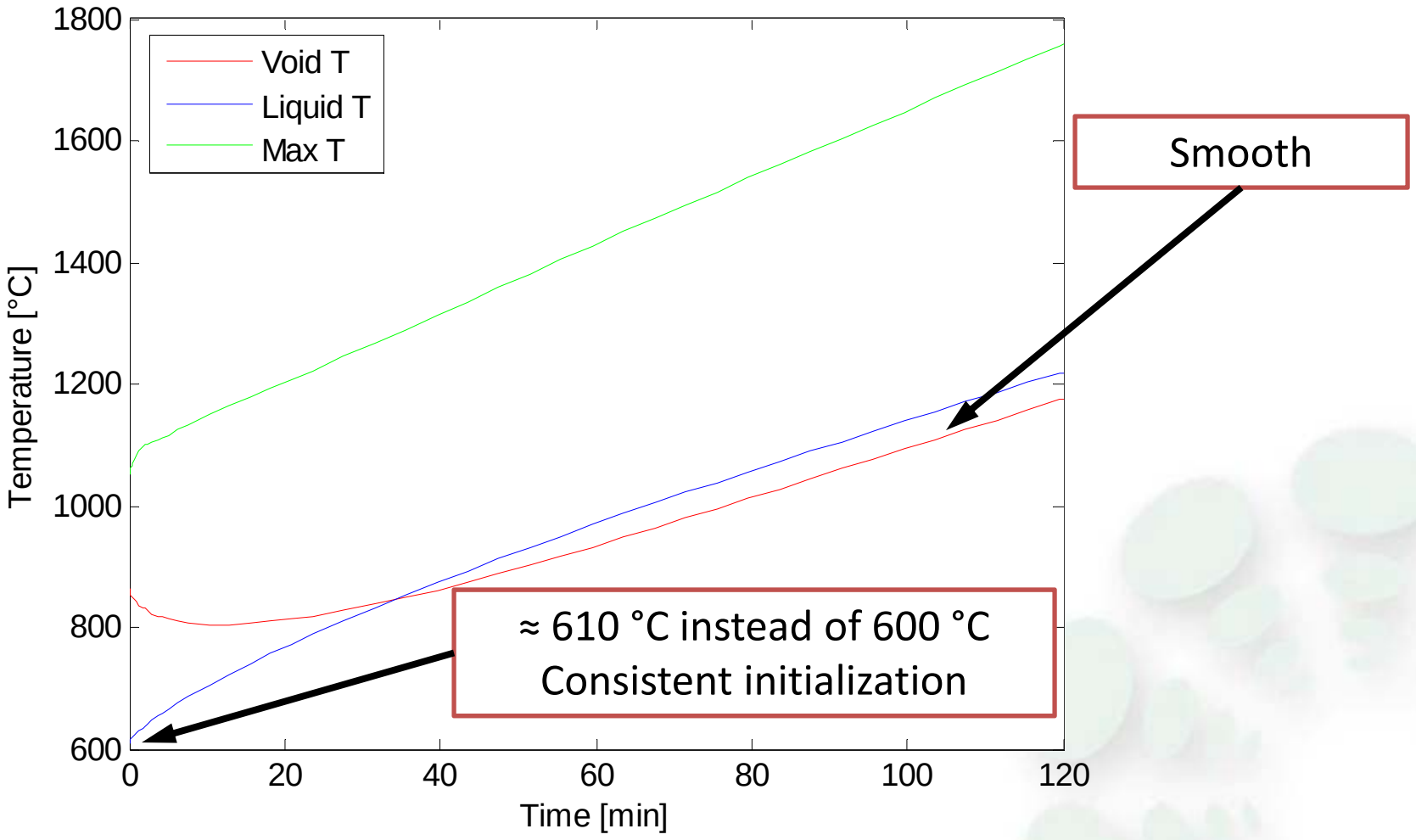
Specified tolerance: ≈ 1 K
Fluctuations (error): ≈ 100 K

Instantaneous Filling
Non-linear tolerance factor 0.1

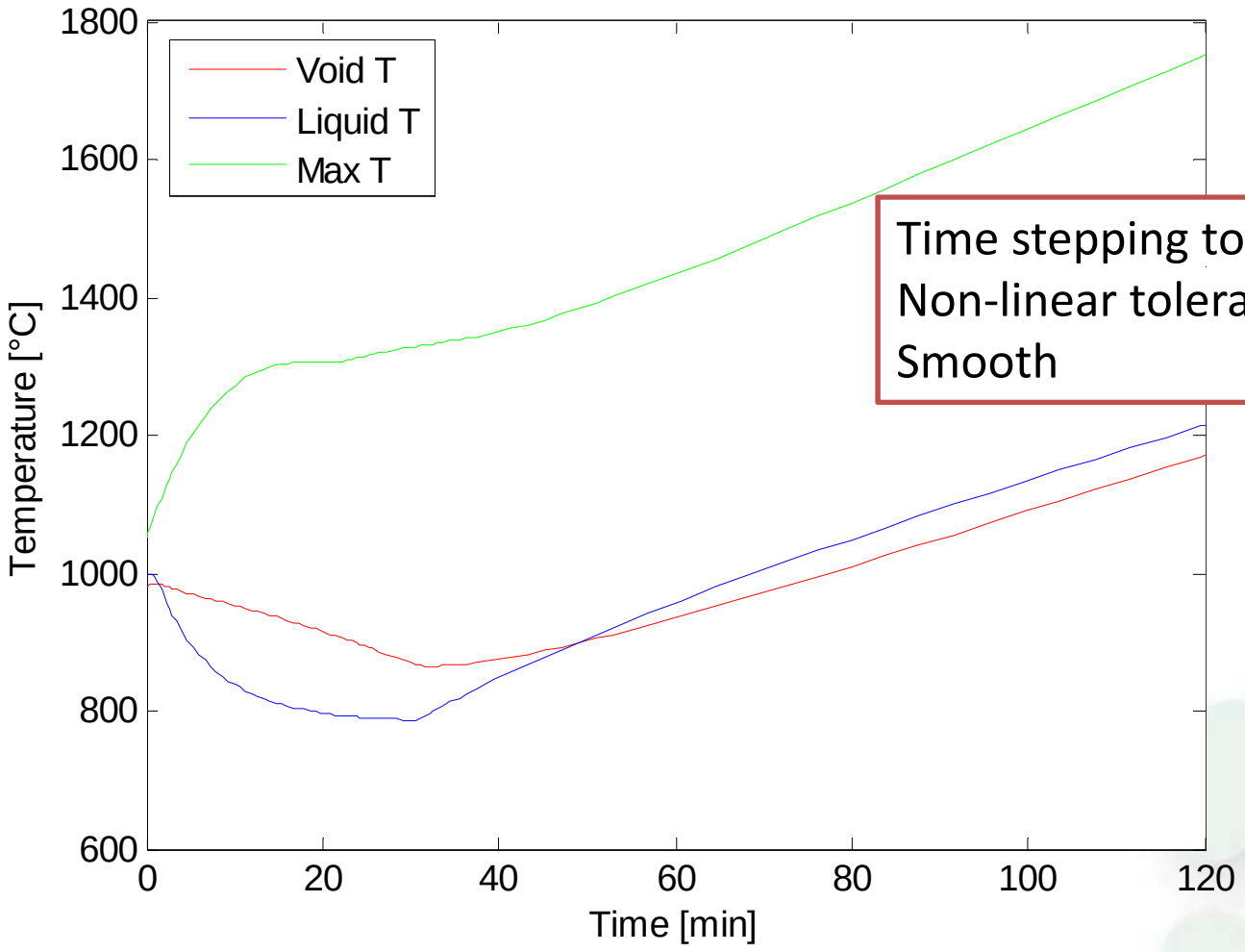


Less fluctuation

Instantaneous Filling
Non-linear tolerance factor 0.01

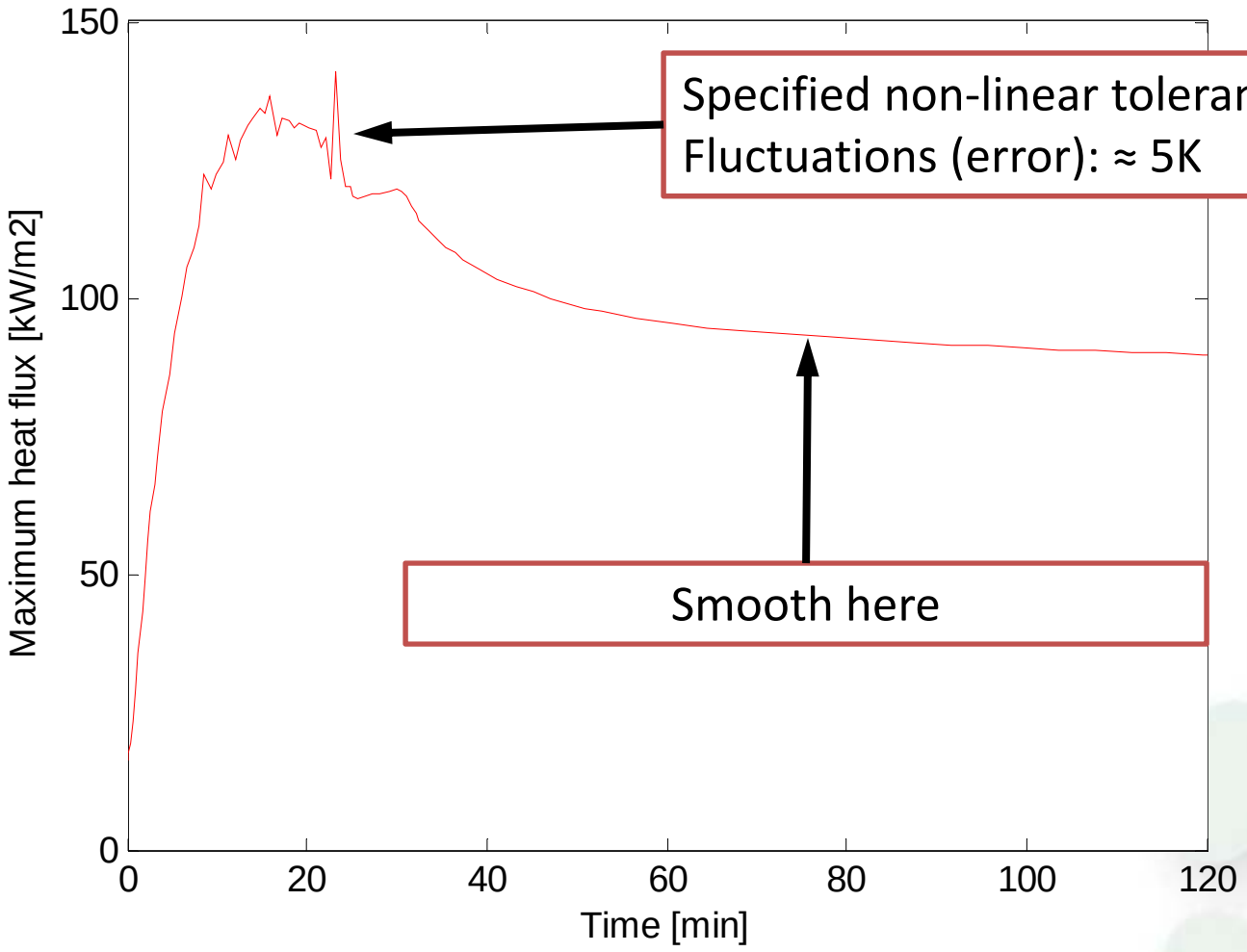


Gradual Filling
Main Temperatures

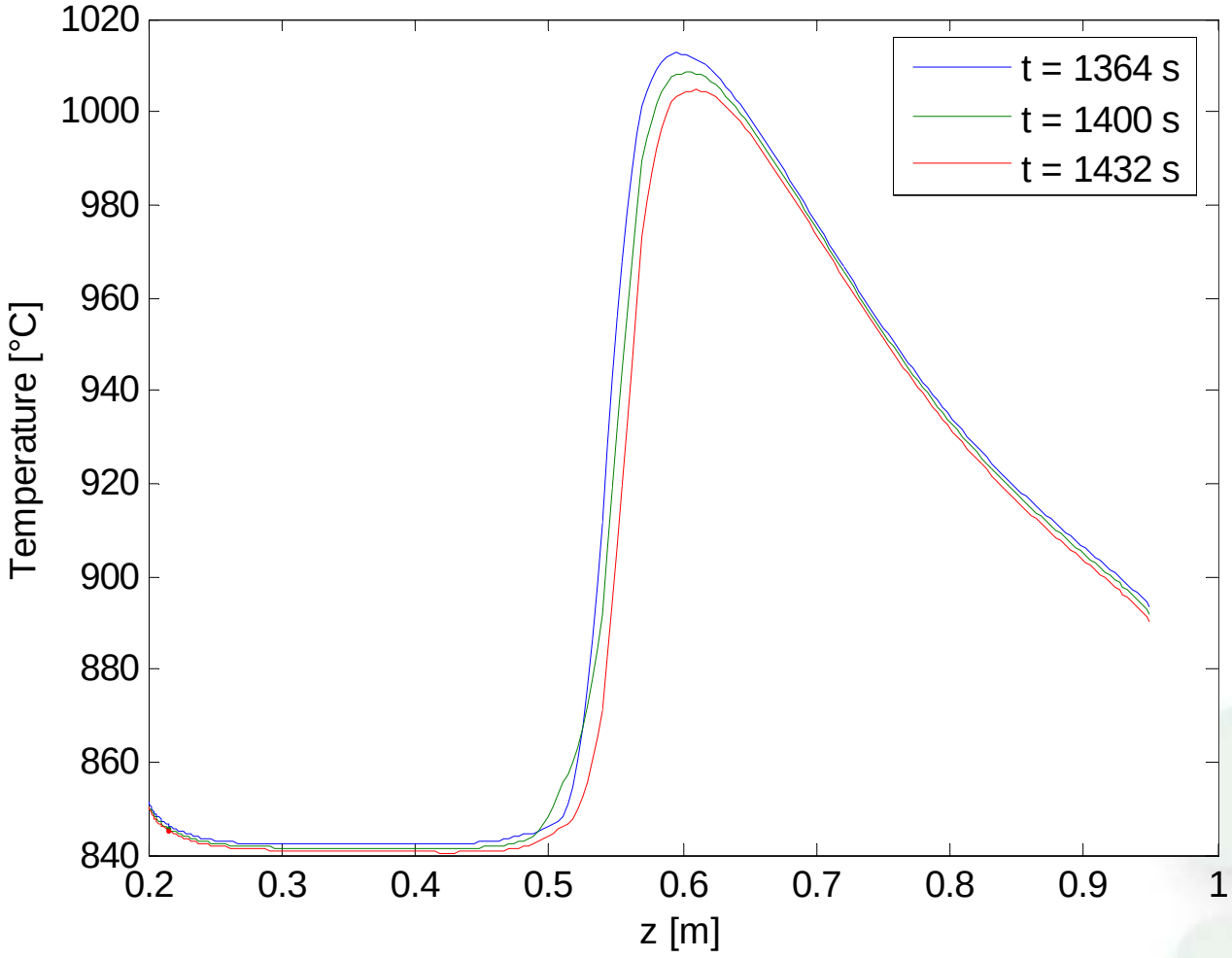


Time stepping tolerance: 0.1 K
Non-linear tolerance: 0.001 K
Smooth

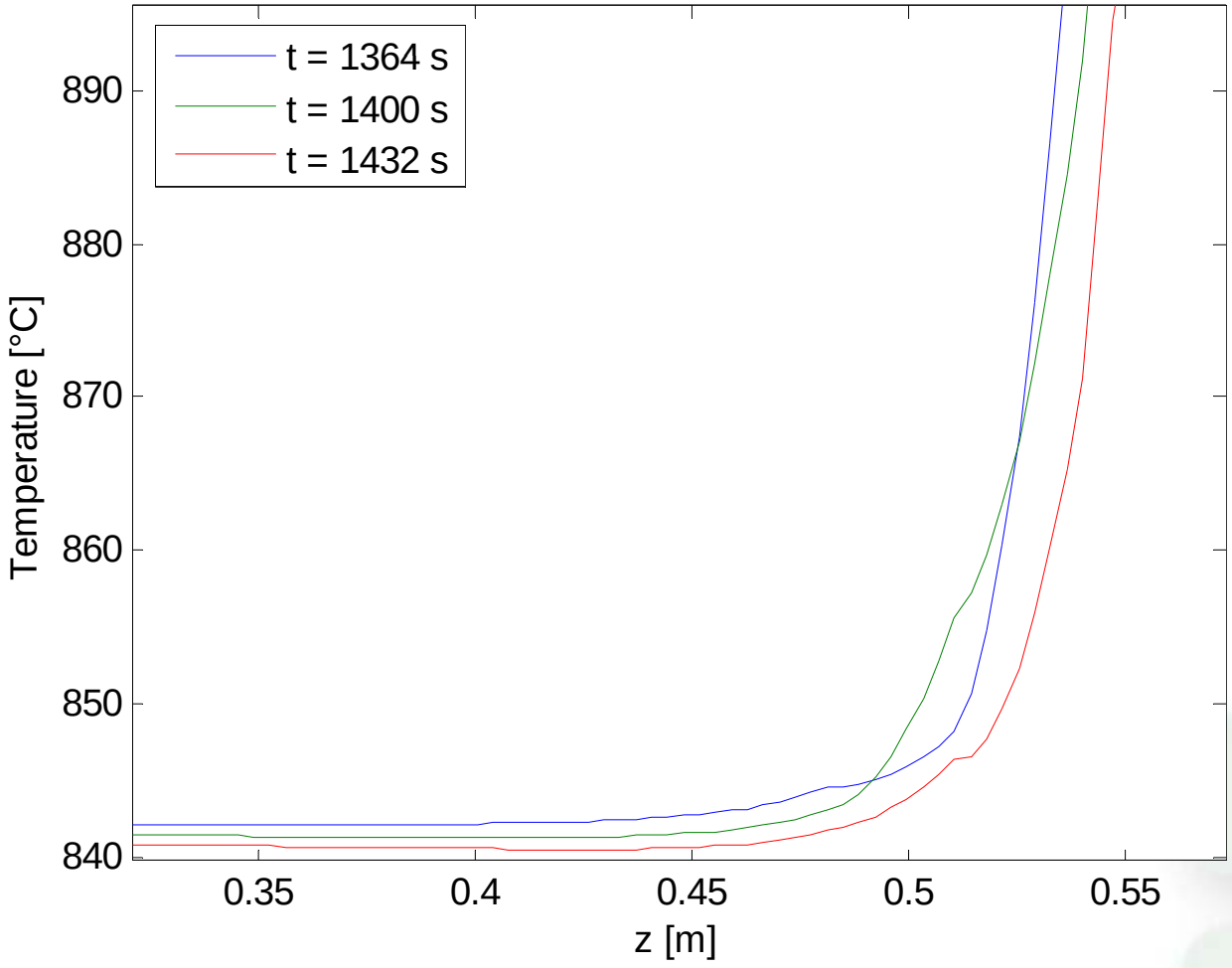
Gradual filling – Example
Maximum inside heat flux



Gradual filling – Example Temperature along crucible



Gradual filling – Example Temperature along crucible



DAE/ODE – Solver problem

- Time integration error – Not tested here
  - Two different methods
  - Compare results
- Non-linear iteration error
  - Need to solve non-linear equations, each time step
  - Some times: Extremely large error in Error estimate
    Not detected!
  - More iterations needed,
    or Jacobian should have been updated

DAE/ODE – Solver problem Solutions?

- Reduce non-linear tolerance factor
  - How much?
  - Inspect for “irregularities”
    - Which variable/expression?
- Force Jacobian update
  - Each time step
  - Each iteration
  - Criterion?
- Unnecessary cost:
  Increased CPU-time whenever not required

DAE/ODE – Solver problem Proposal

- Additional criteria for non-linear iterations
- User specified

- Overall heat balance (material balances, etc.)
- Demand high accuracy for the heat balance

- Further research needed

Conclusions – Model

- ”A Model for High Temperature Inductive Heating” – Successfully developed
- COMSOL Multiphysics is suitable

- Model provides valuable insight
- When lumped variables are included: Consider smoothing
  - Physics – More relevant approximation
  - Numerics – Considerably decreased CPU-time

Conclusions – Numerics

- Special care/procedures are needed
- DAEs: Initial time step influences initial accuracy
- Estimate for non-linear iteration error
  can be highly inaccurate
  $\Rightarrow$ Error in solution – can cause divergence
  - Now:
    Apply more strict non-linear tolerance
    Inspect suitable expression for non-physical fluctuations
  - Proposed:
    Utilize overall balances
    User specified tests