Svenn Anton Halvorsen, Nora Kleinknecht: An Improved Model for High Temperature Inductive Heating

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Stuttgart

Inductive Heating Improved Model

- Multiphysics model
  - Heat Transfer
  - ODEs and DAEs – Simplifications, constraints, control
  - Magnetic Fields – "Complex pollution" of real variables
  - Solid Mechanics – Thermal stresses, displacements
- Improvements and experience
  - Model improvements
  - COMSOL versions – 3.4, 3.5a, 4.0a, 4.1, 4.2
    Some problems, experience, improvements
  - Case studies, current control

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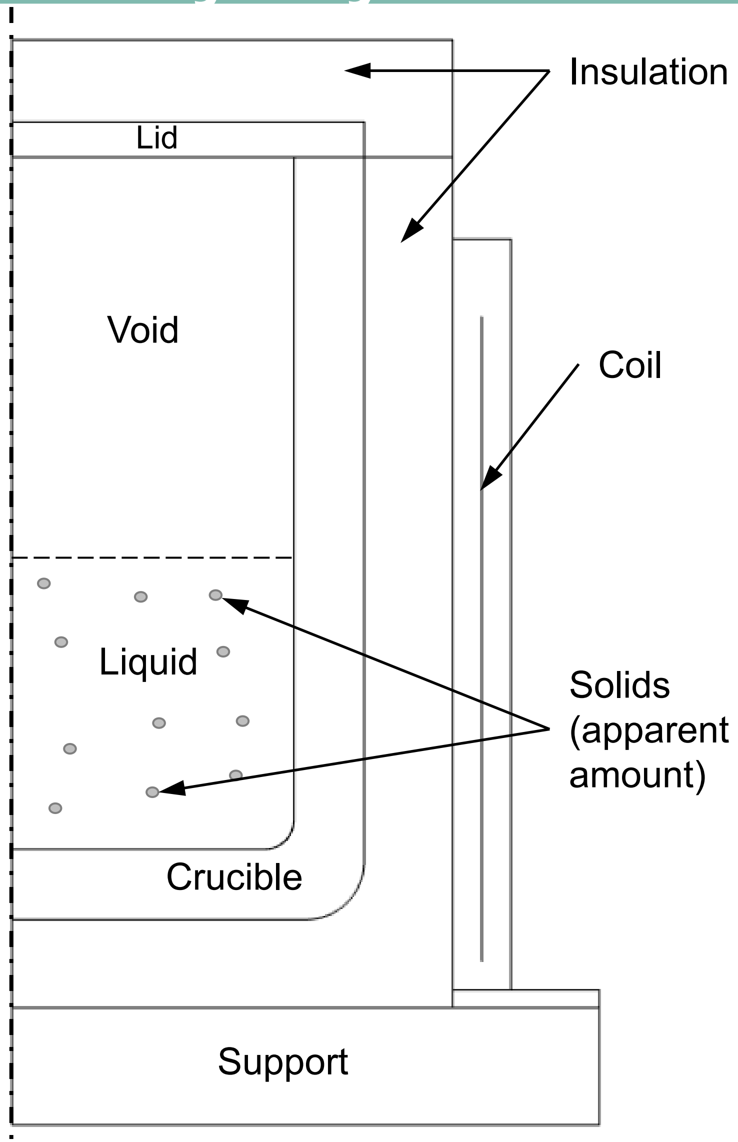
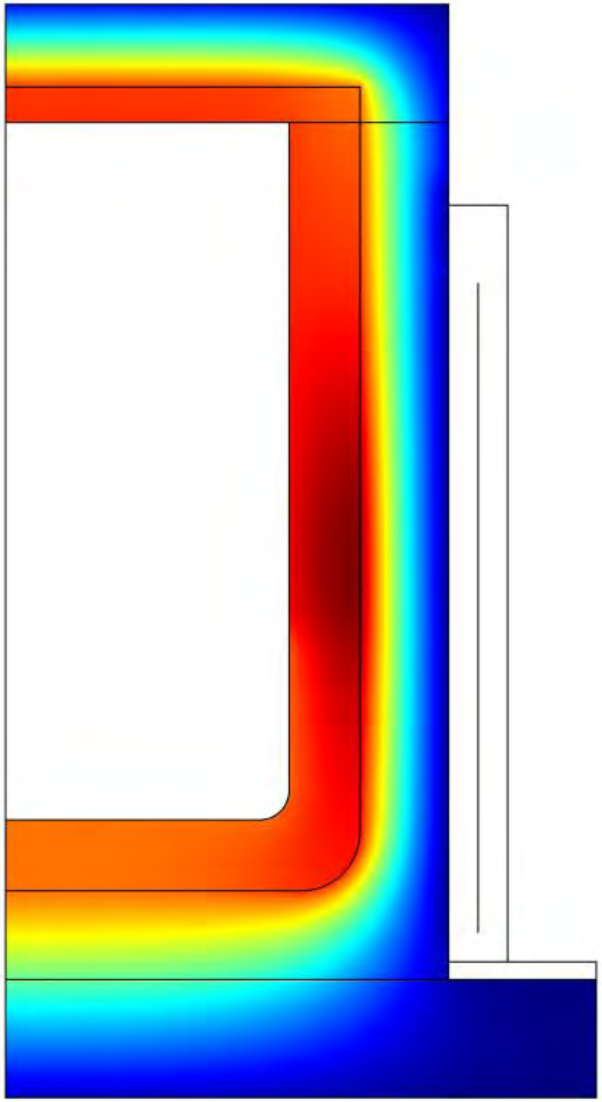
High Temp Inductive Heating Axially Symmetric Model



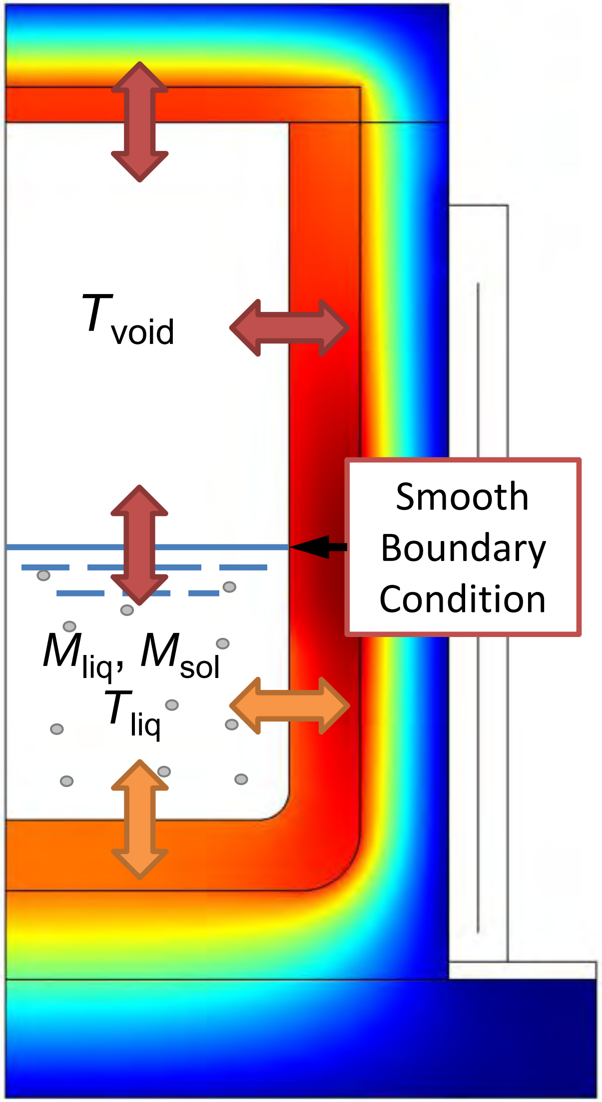
- Case study: Melting
- Non-conductive liquid
  - Crucible heated by induction
- Conductive liquid (metal)
  - Non-conductive crucible

Multiphysics
Heat Transfer



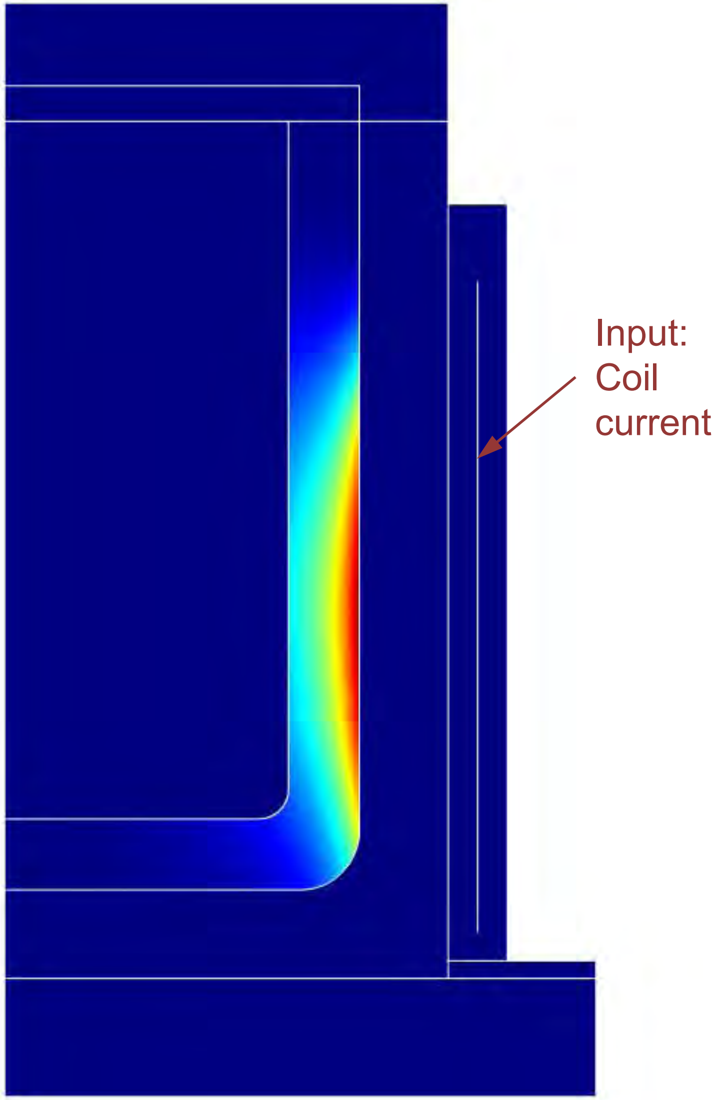
- Crucible, lid, insulation, support
- Induced power
  - Electromagnetics
- Outside: Boundary conditions
- Inside: Couple to void and liquid

Multiphysics, ODEs and DAEs, Discrete state variables



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

Multiphysics Magnetic Fields



- Power distribution
  - Input to heat equation

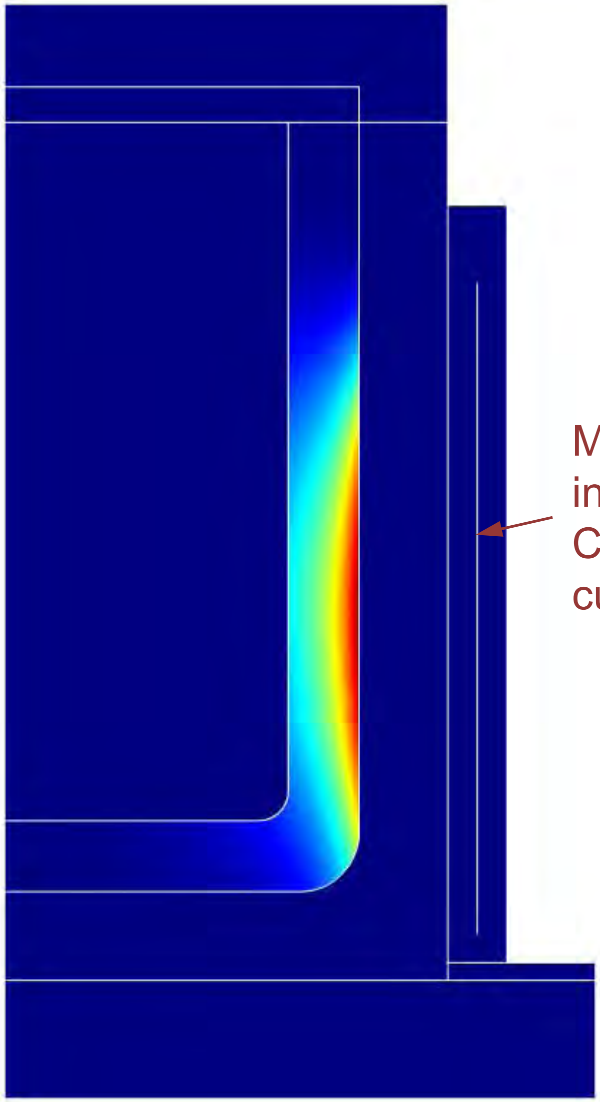
$$Q_{\mathrm{rh}} = \frac{\mathrm{Re}(\mathbf{E} \cdot \mathbf{J}^*)}{2}$$

- AC, frequency domain
  - Complex fields
  - Re(z) non-analytical (no derivative!)
  - Non-linear solver applies Jacobian (derivatives)

Magnetic Fields
Coupling to Heat Transfer

- Previously
  - Pseudo Jacobian
  - BUT: "Complex pollution" (small imaginary components)
    - Temperatures
    - Mechanical stresses
    - …
  - Computational problems!
- From version 4.1
  - Ignore Jacobian information (magnetics $\rightarrow$ heat transfer)
  - Segregated solver
  - OK for weak couplings

Magnetic Fields, ODE/DAEs Coupling to Heat Transfer



Model input: Coil current

- Specified power

$$\iint 2\pi r\, Q_{\text{induced}}\, drdz = W_{\text{SetPt}}(t)$$

Total induced power = Set point value

- Temperature given

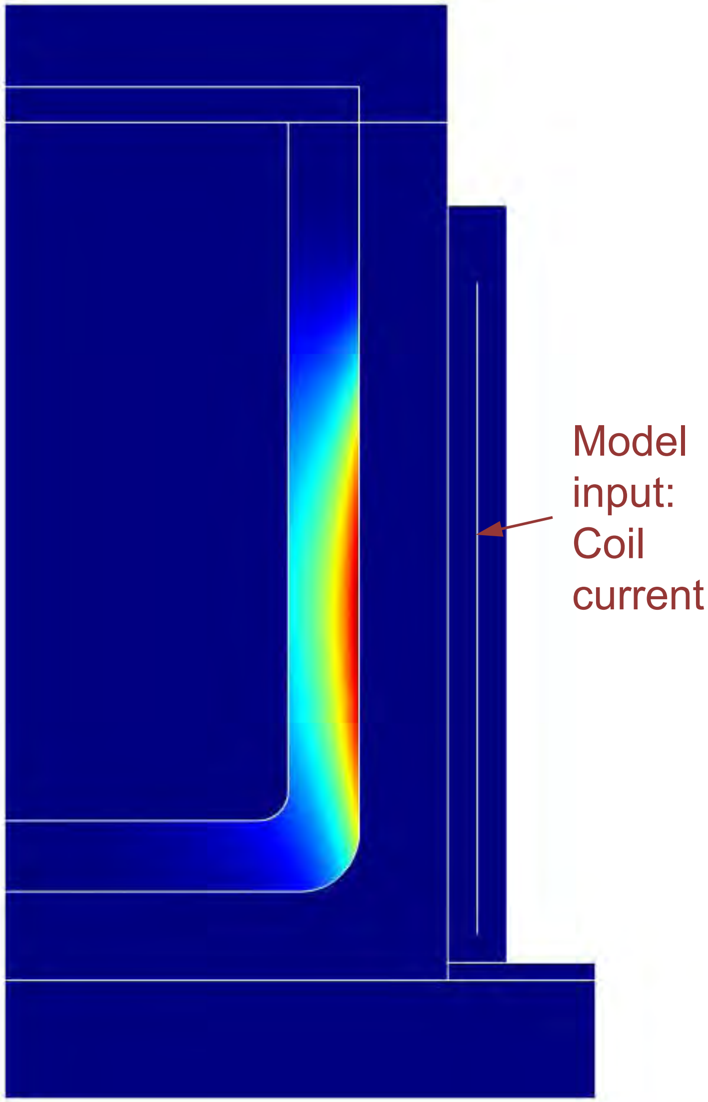
$$T_{\text{Chosen}}(t) = T_{\text{SetPt}}(t)$$

A computed T = Set point value

- I_{coil} is complex !

Magnetic Fields, ODE/DAEs Coupling to Heat Transfer

teknova

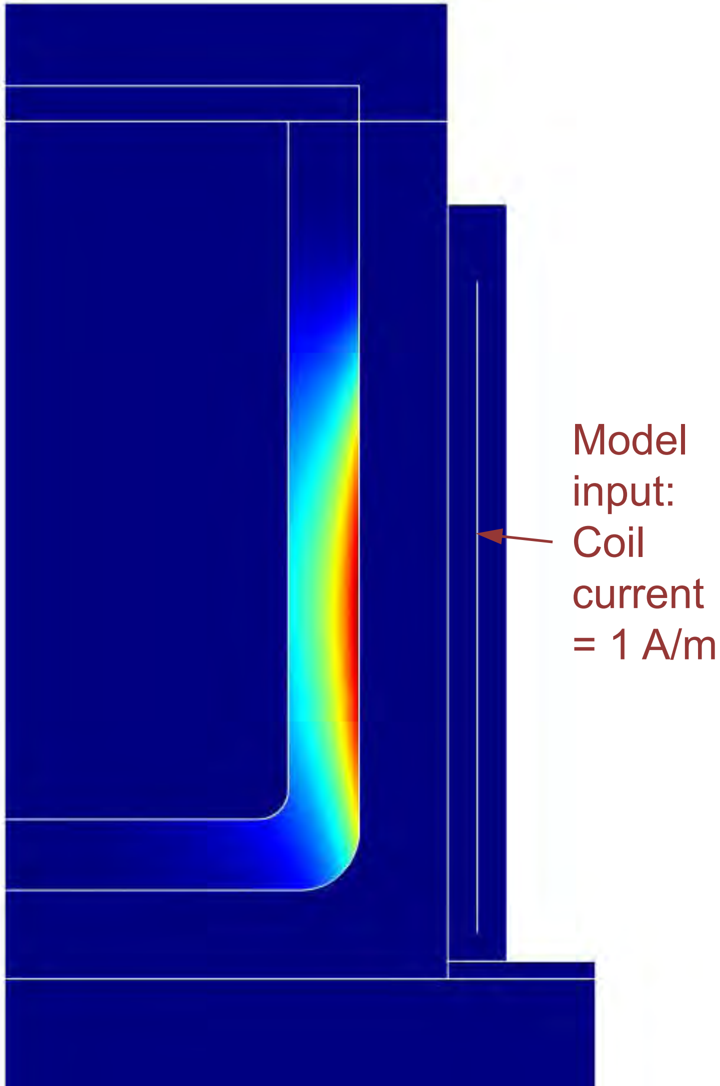


- Equation for I_{coil}

  Total induced power = Set point value
  or
  A computed T = Set point value

- v 4.0a: Pseudo Jacobian
  - Phase angle is undetermined, but get "Solution" ! Dynamic problems !
  - Fix: Modify equation
- v 4.1: No Jacobian info
  - One missing equation
  - No computations

Magnetic Fields, ODE/DAEs Coupling to Heat Transfer



- Equation for I_{coil}

Total induced power = Set point value
or
A computed T = Set point value

- Quadratic dependence, move I_{coil} "outside" electro-magnetics

$$Q_{\text{induced}} = I_{\text{coil}}^{2}\, Q_{\text{rh}}$$

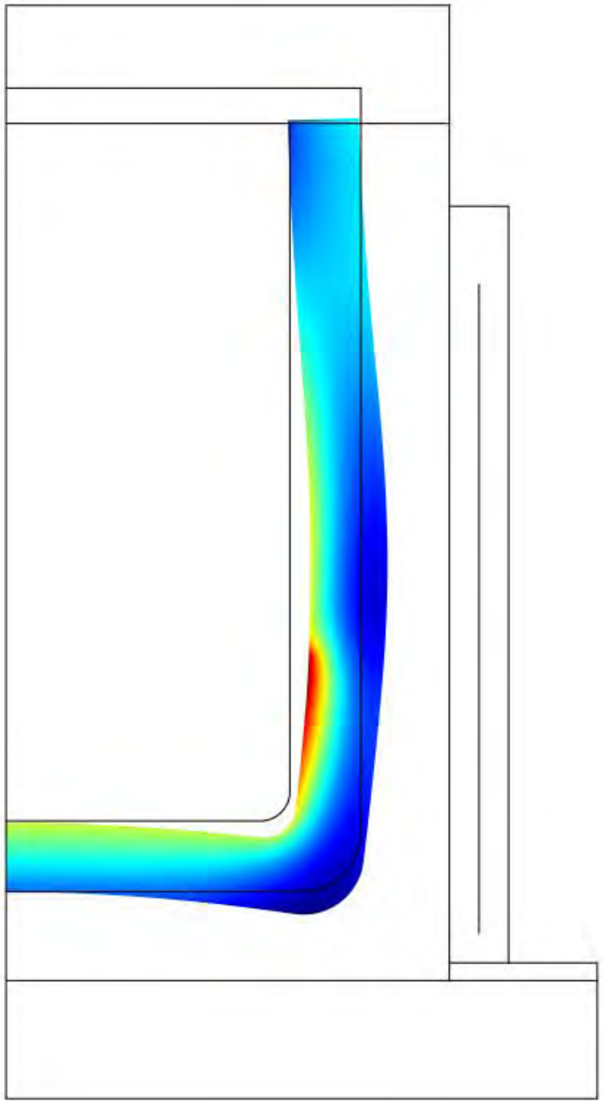
Input to the heat equation

Due to 1 A/m coil current

Magnetic Fields, ODE/DAEs Coupling to Heat Transfer

- Latest info from COMSOL – Version 4.2a
  - Declare fields as complex or real
  - Split AC (complex) fields into real and imaginary parts (at solver level)
    Equivalent to using real valued sine and cosine terms
  - Constrain phase of ODE (feedback control) variables

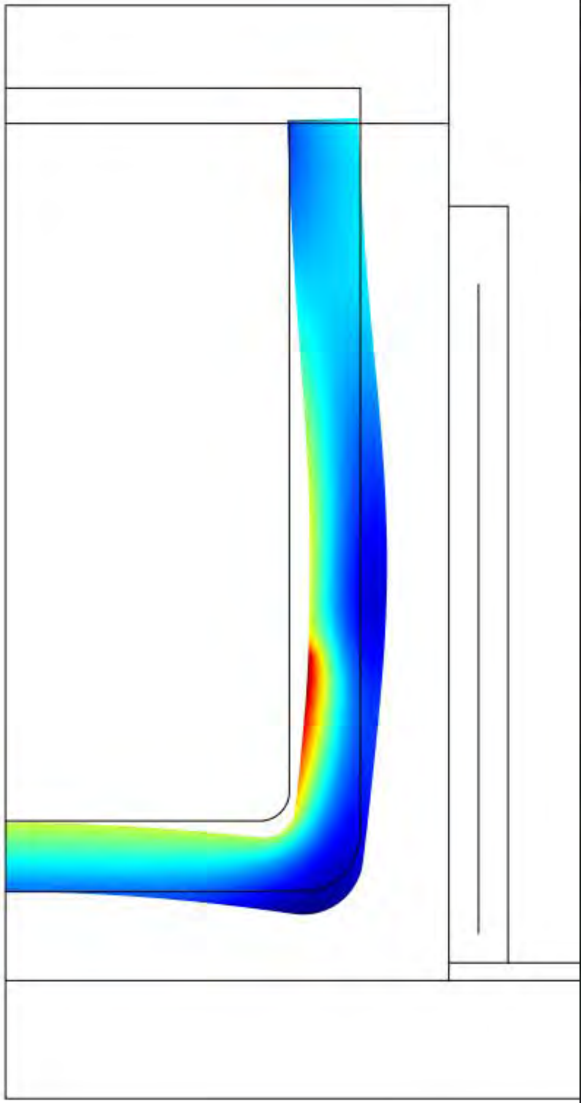
Multiphysics
Solid Mechanics

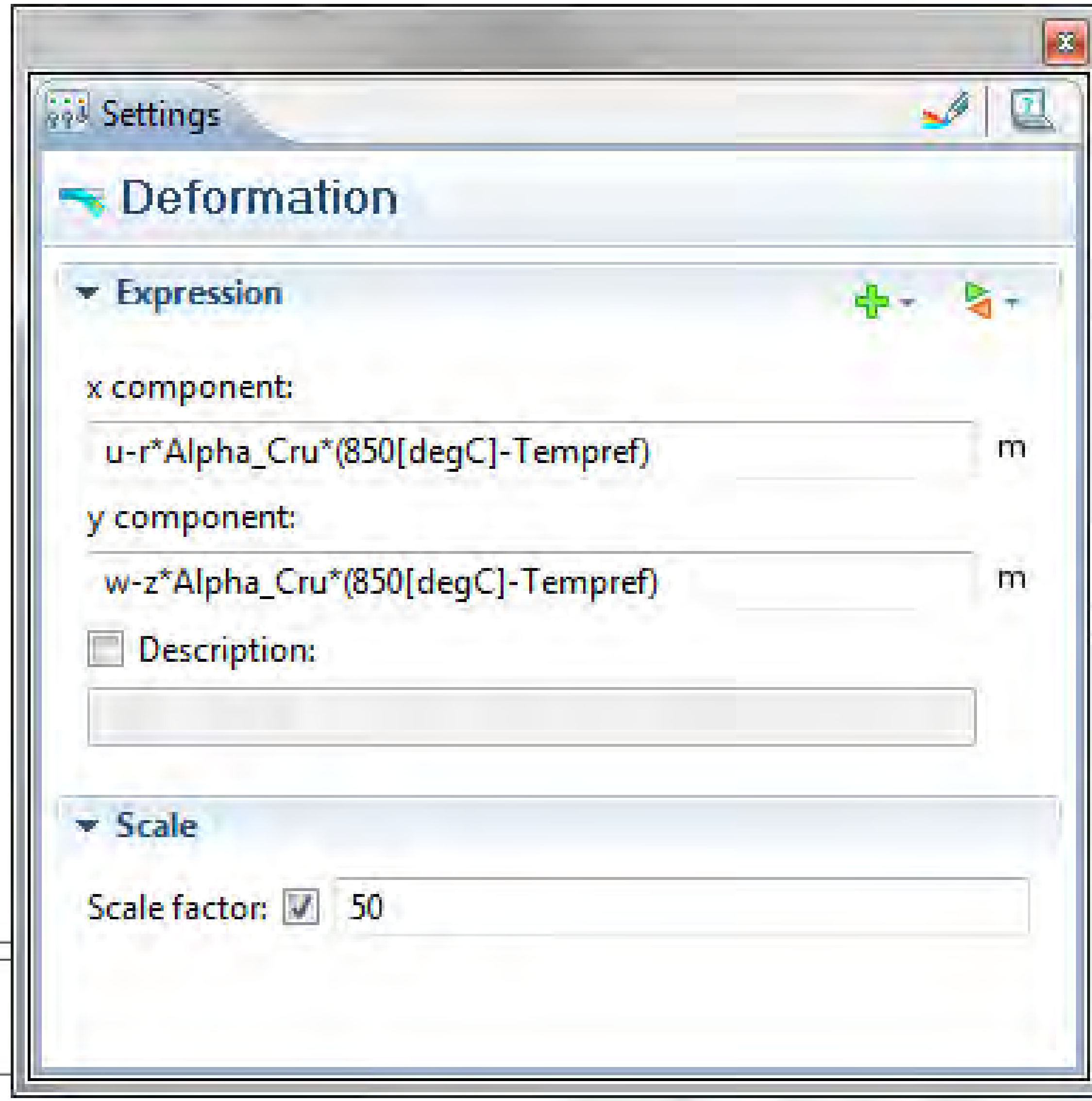


- Crucible only
- Insulation is soft

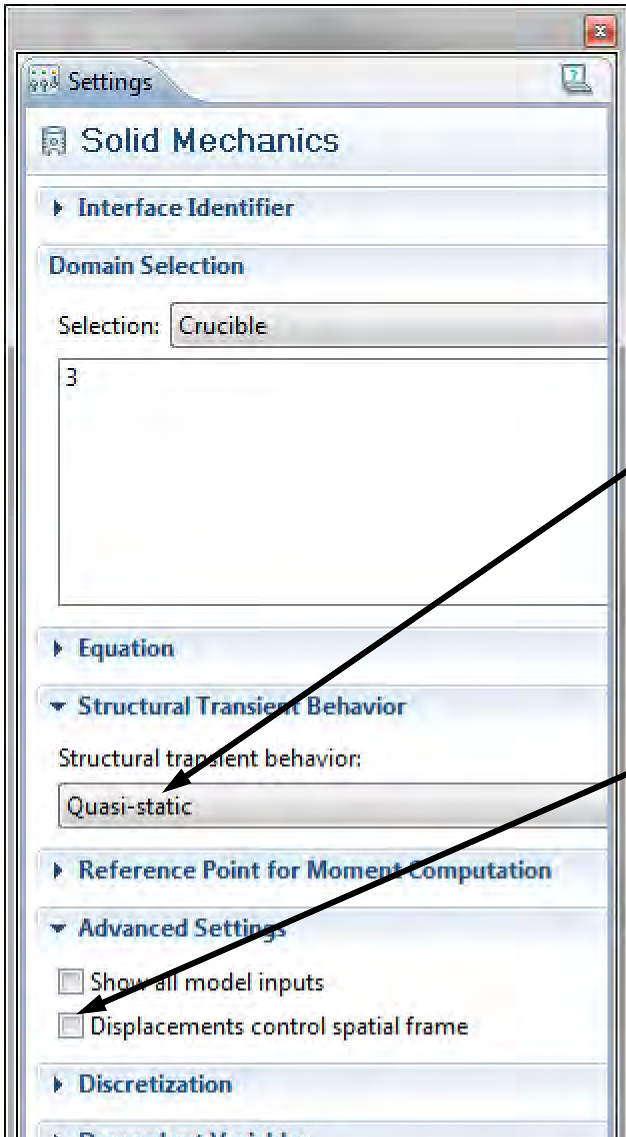
- Example: Stress in the angular direction
  - Deformation, relatively to expansion at 850 °C
  - Scaled 50 times

Multiphysics
Solid Mechanics





Multiphysics
Solid Mechanics, Settings v 4.2



- Structural transient behavior:
  - Quasi-static
- Advanced Settings
  - Uncheck: Displacements control spatial frame

Improvements

- Quasi-stationary melting:
  Slow process, drop d/dt terms
  - Significant: Heating and melting of solids
  - Insignificant: Change of local T, T_{liq}, T_{void}
  - Required:
    charging/input rate = melting rate
- Conductive or non-conductive liquid
- Far more complex dynamics
- Control: specified power or temperature, combined (power plus proportional T-control)

Conclusions

- Model for High Temperature Inductive Heating
  - Previously: Successfully developed
  - Successfully migrated
    - From version 3.4
    - Via versions 3.5a, 4.0a, and 4.1
    - To version 4.2
  - Successfully improved
- COMSOL Multiphysics is a suitable tool

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