NUMERICAL INVESTIGATION OF NON-ISOTHERMAL AXIAL SLOSHING OF LIQUID METHANE

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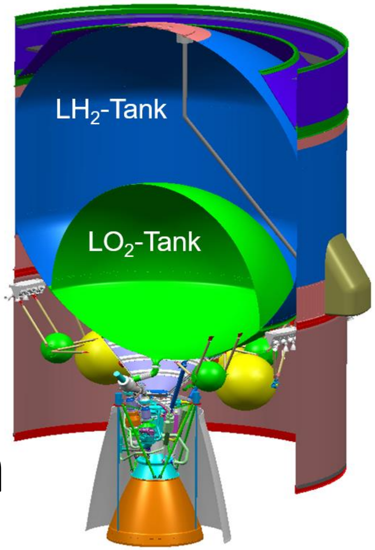
Introduction

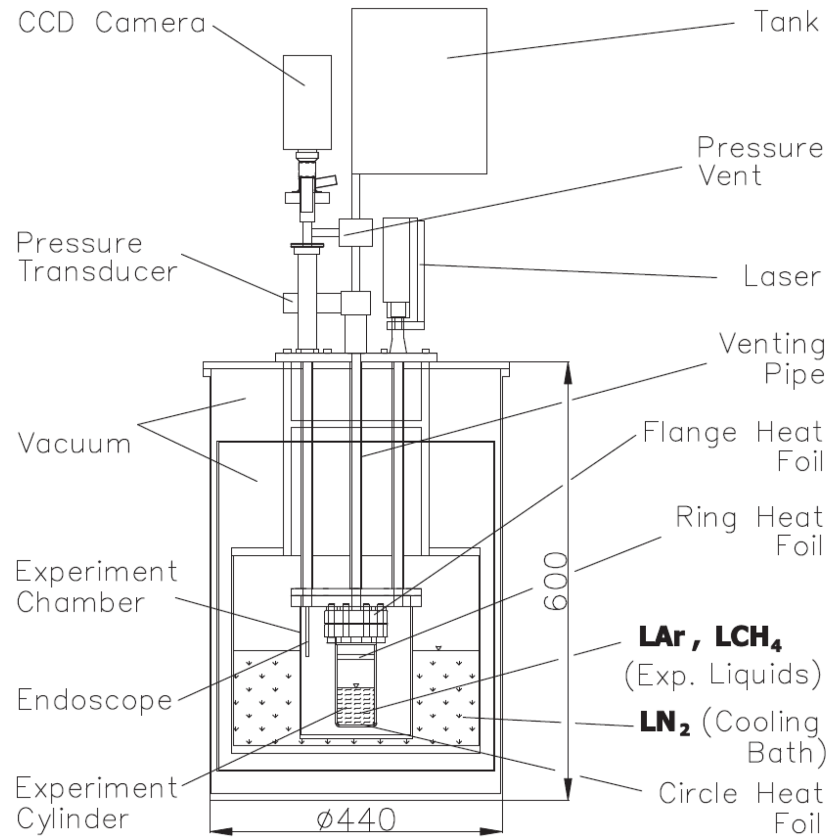
- Cryogenics as rocket fuel
  - Phase change and liquid position of importance
- Main engine cut off leads to a step reduction of accelaration
- Axial sloshing might occur
  - Numerical simulations to investigate
  - Validate against experiments

(Kulev et al., Cryogenics 62 48-59, 2014)



Experimental Setup

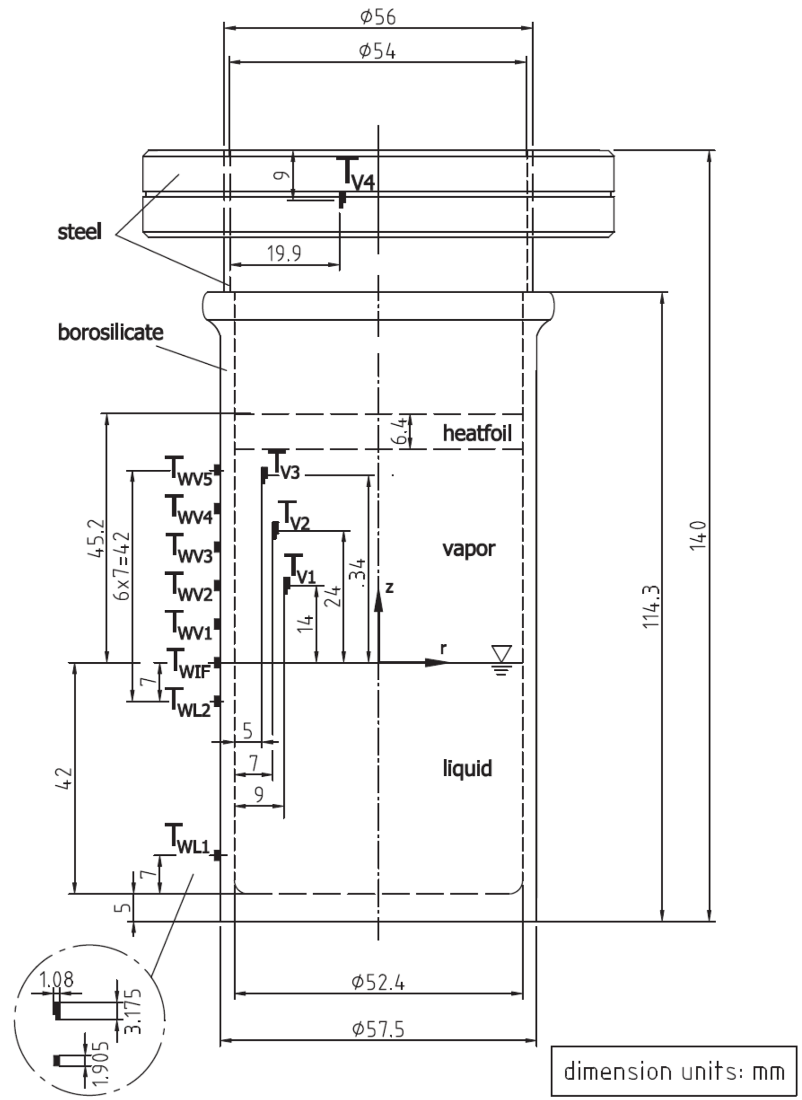
- Reorientation of liquid is observed
- 4.7 s of compensated gravity
- Glass cylinder is partially filled with liquid methane
- Pipes and tank filled with gaseous methane
- Pressure, temperature & video are recorded



Experimental Setup

Radius	Fill height	P_0	$T_{sat}(P_0)$
26.2 mm	42 mm	47 771.5 Pa	103.26 K

- Heaters at top and bottom
  - Bulk liquid heated to saturation condition
  - Axial temperature gradient in wall

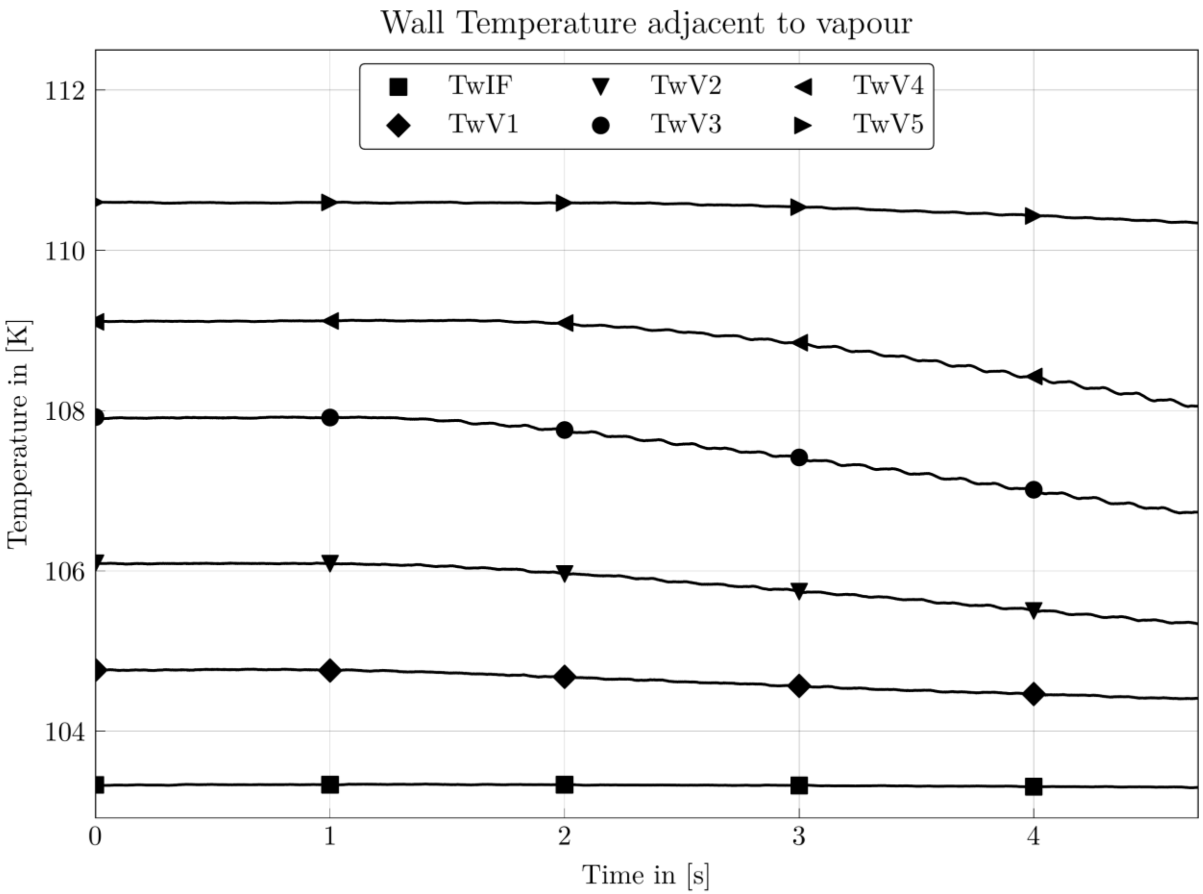


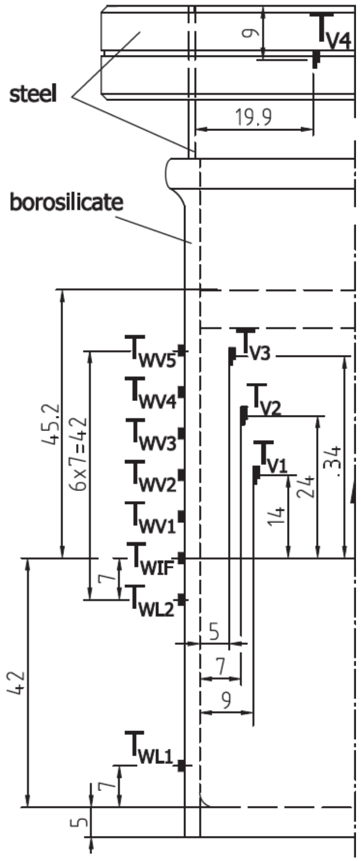
Experimental Results

- Reorientation from:
  high Bo $\Rightarrow$ low Bo
- Damped oscillation of center point
  - Exact absolute position unclear
  - Frequency measurable
- Wetting of wall

Experimental Results

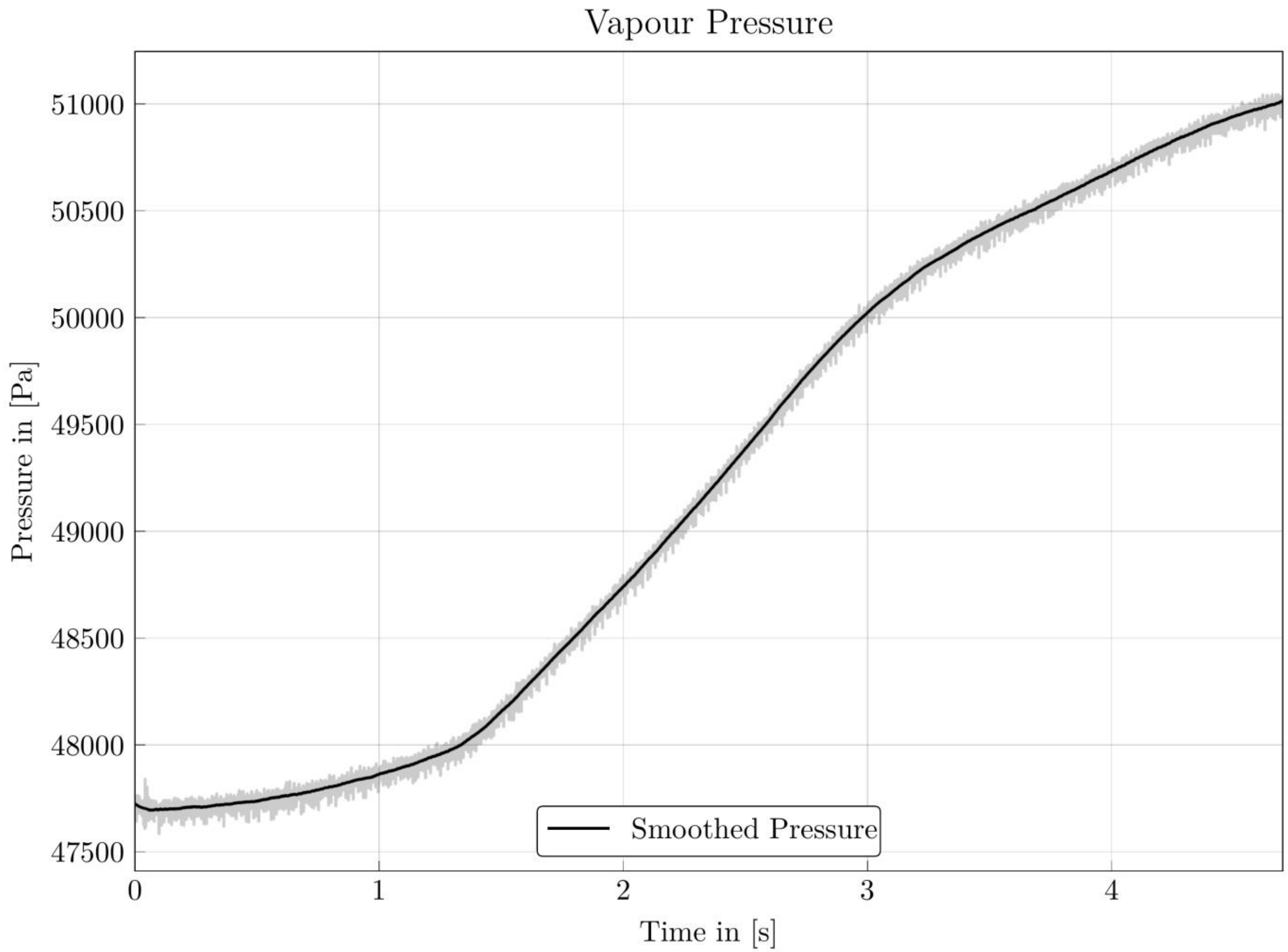
- Wall temperature decreases after contact with liquid methane





Experimental Results

- Increase of vapour pressure



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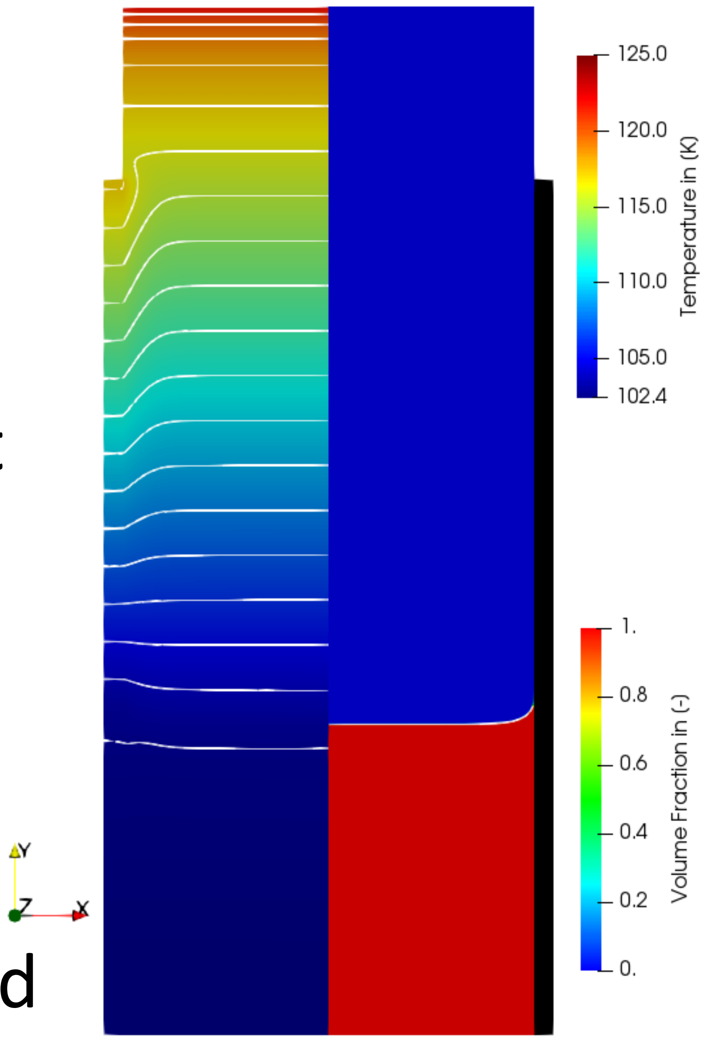
Numerical Tools

- In-house development of OpenFOAM VoF multiphase solver
- Extended by:
  - Weakly compressible treatment of gas phase
  - Phase change model
  - Conjugated heat transfer model

Numerical Setup

- Wedge mesh
- Solid & fluid region
- Conjugated heat transfer
- Linear temperature gradient in vapour and wall
- Fluid at rest
- Rise at wall from prev. simulation
- Connecting volume modelled on top of glass



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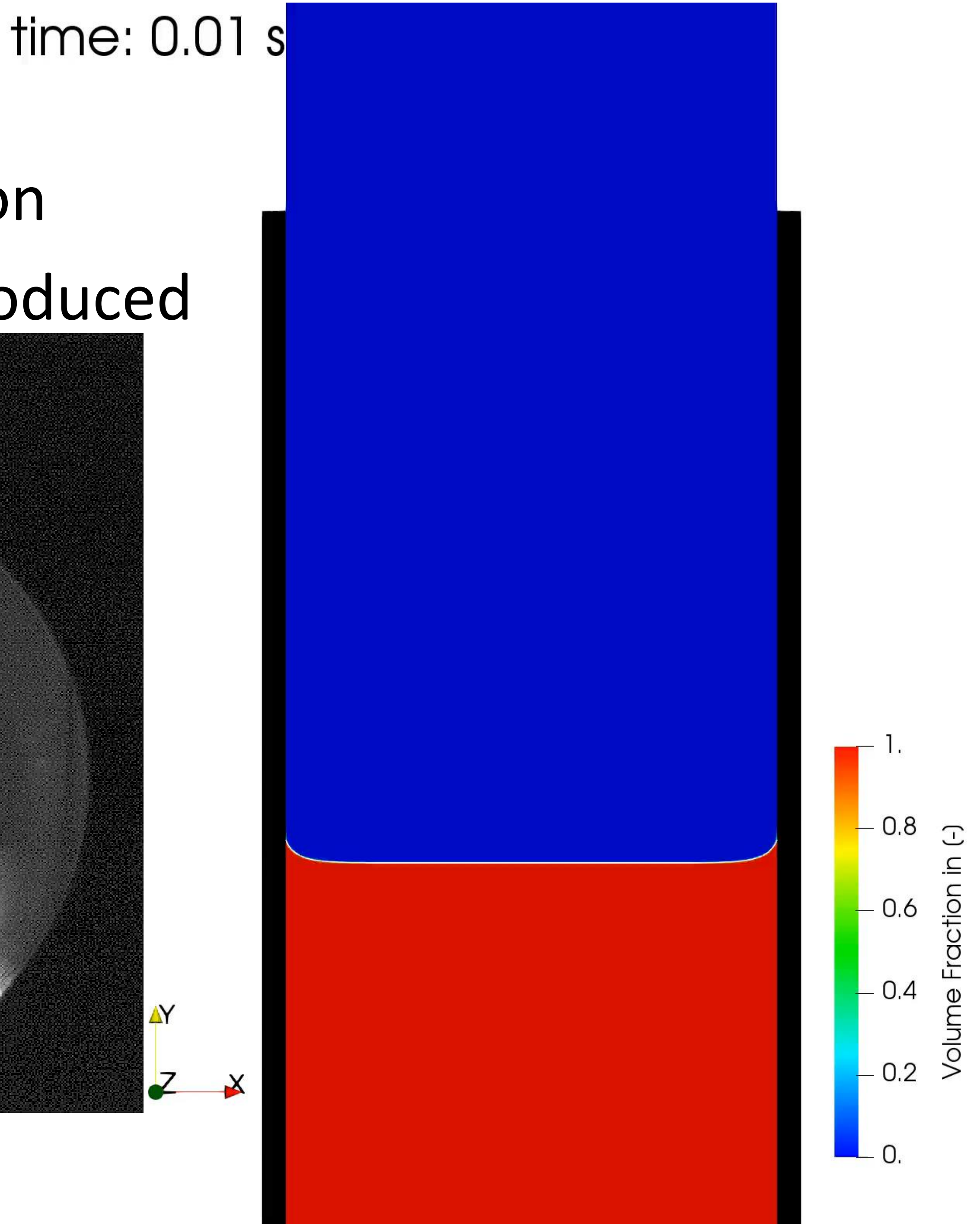
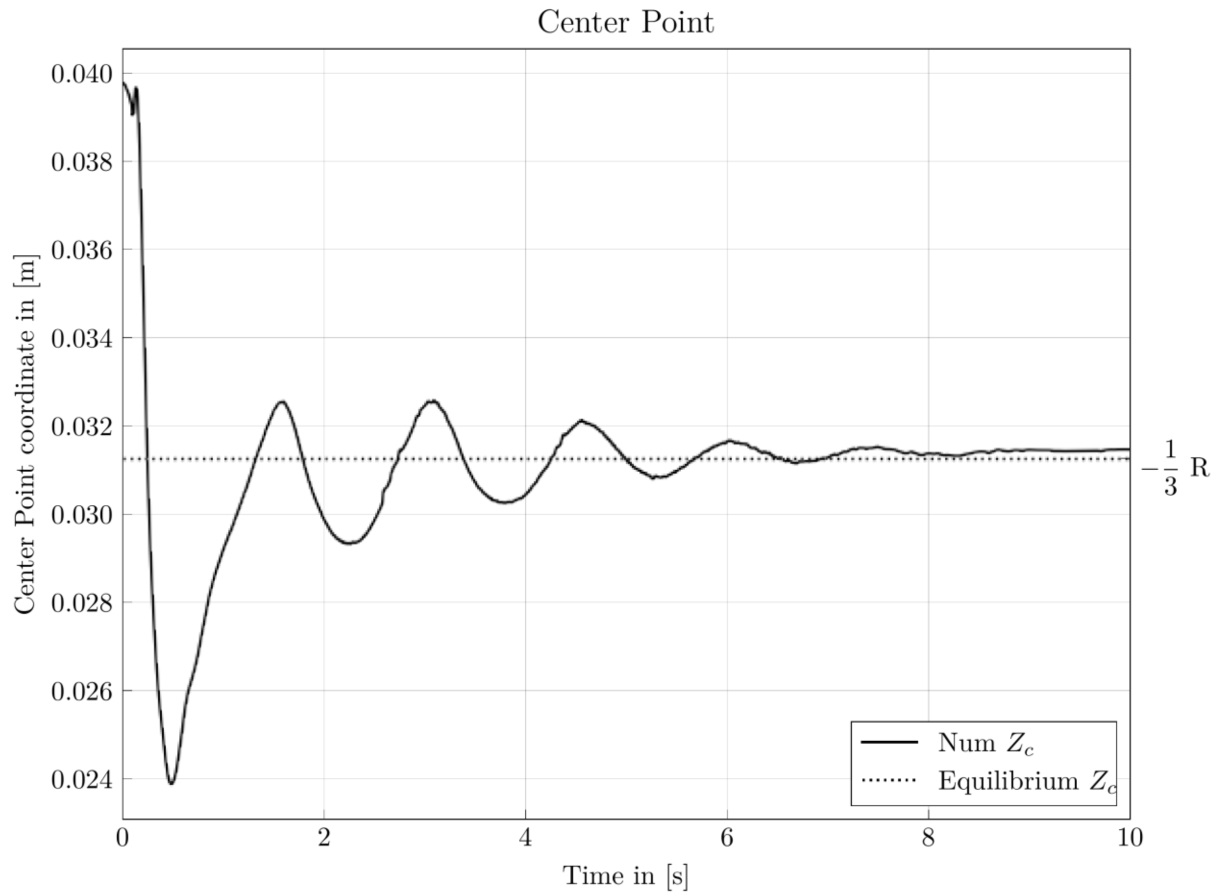
Numerical Results

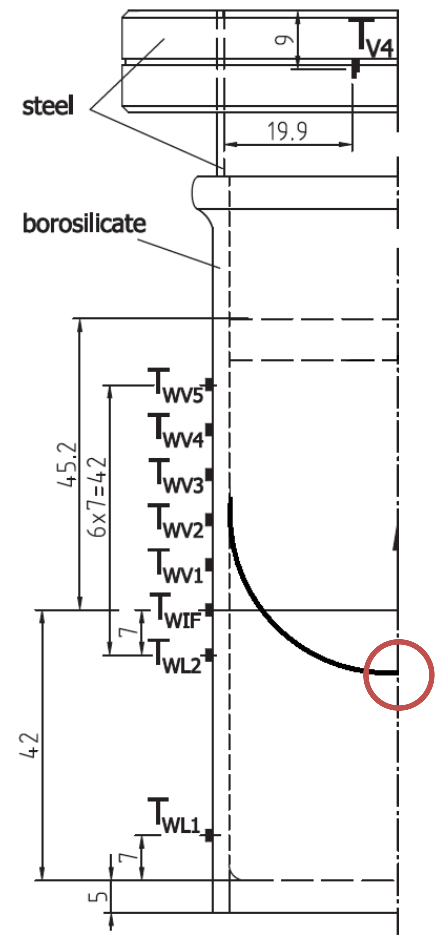
- Damped oscillation of interface reproduced



Numerical Results

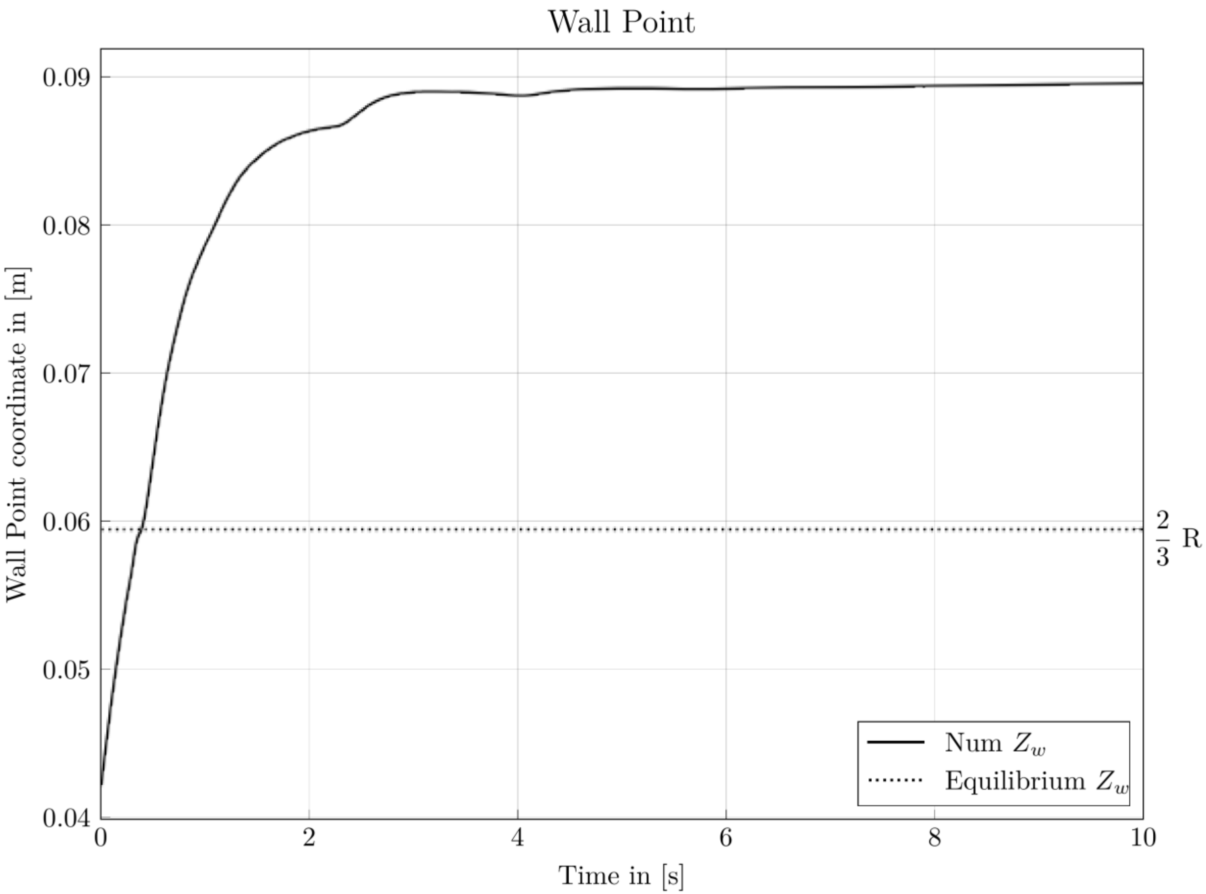
	Experiment	Numeric
Frequency	4.689 Hz	4.217 Hz

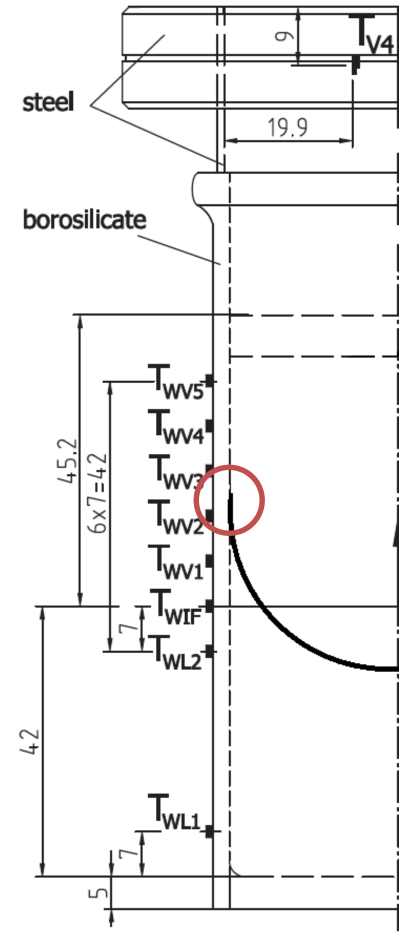




Numerical Results

- Wall rise overshoots equilibrium





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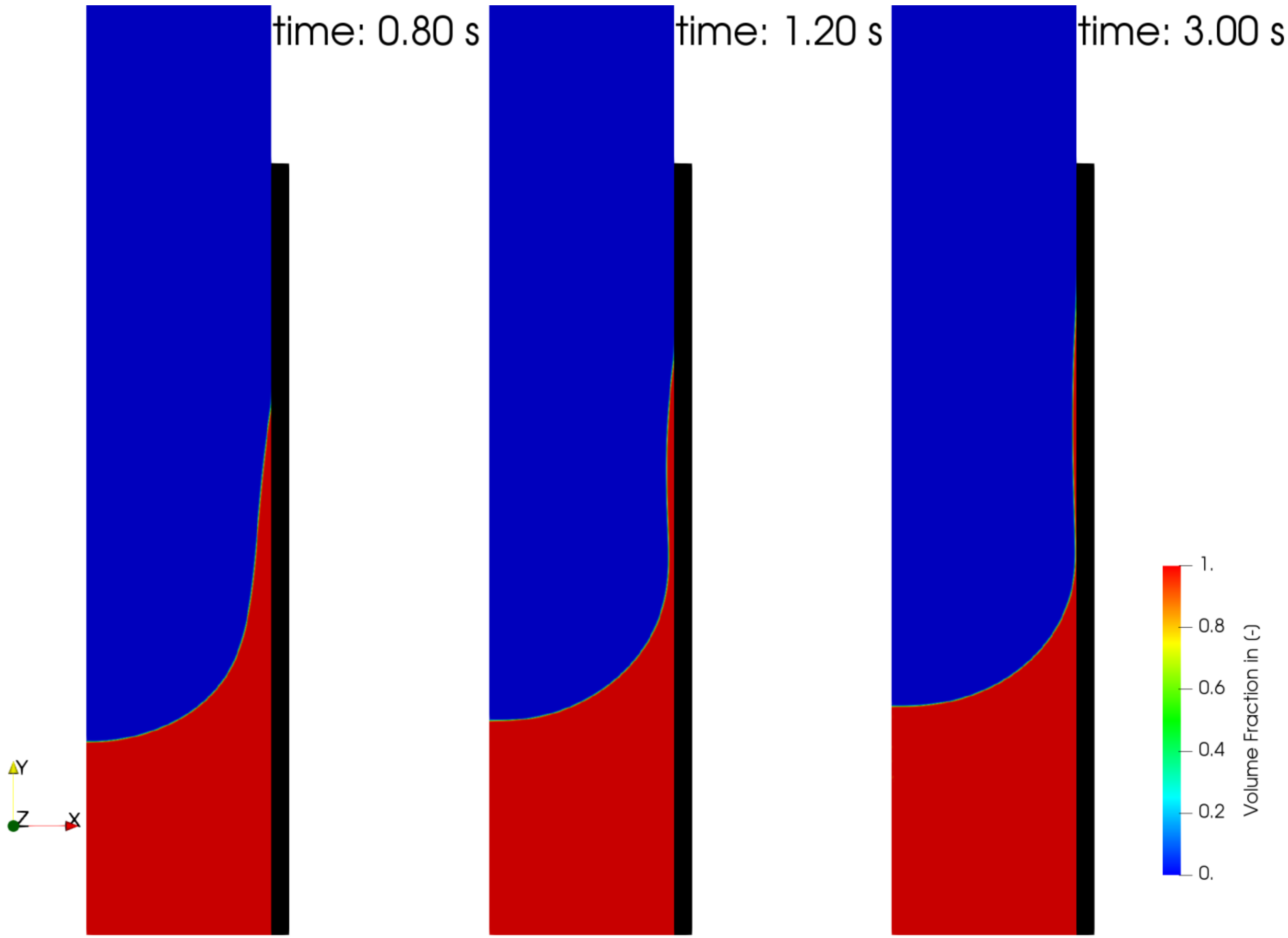
Numerical Results

- Liquid film at wall is formed



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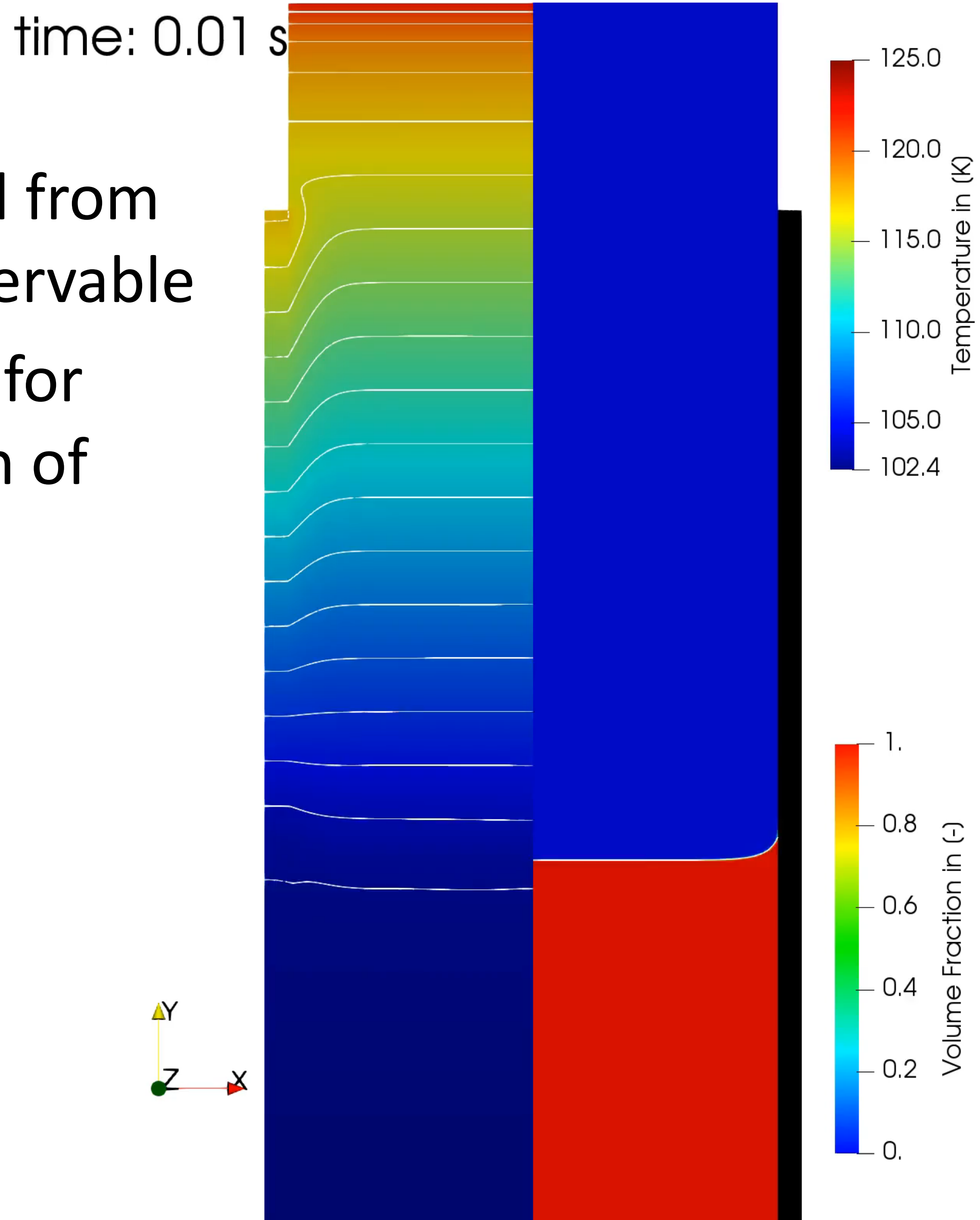
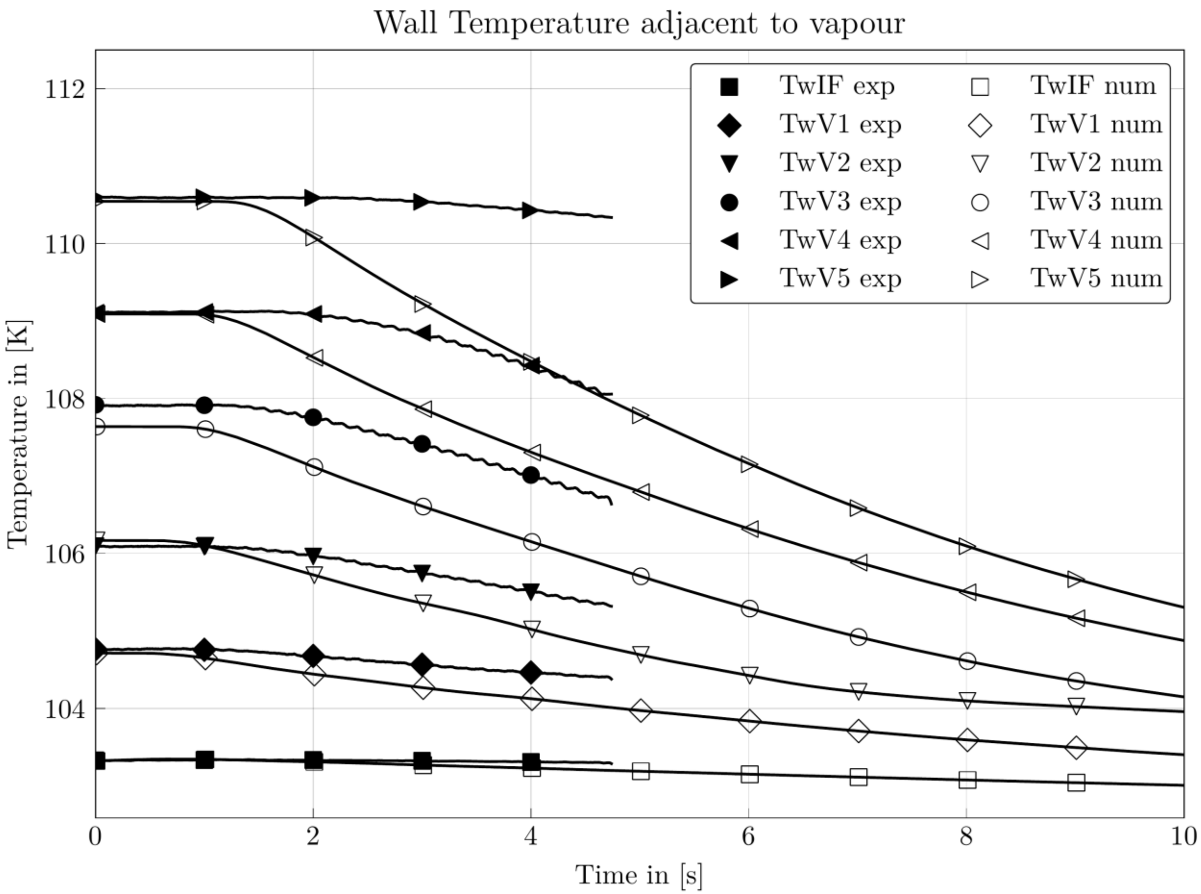
Numerical Results

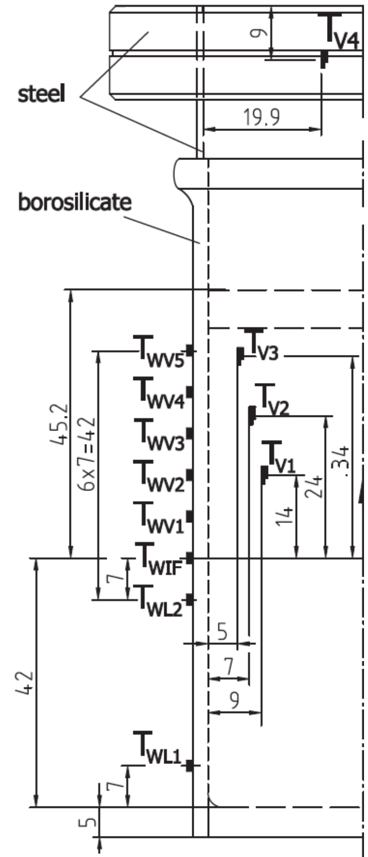
- Heat transfer wall from wall to liquid observable
- Film is influential for thermal condition of wall



Numerical Results

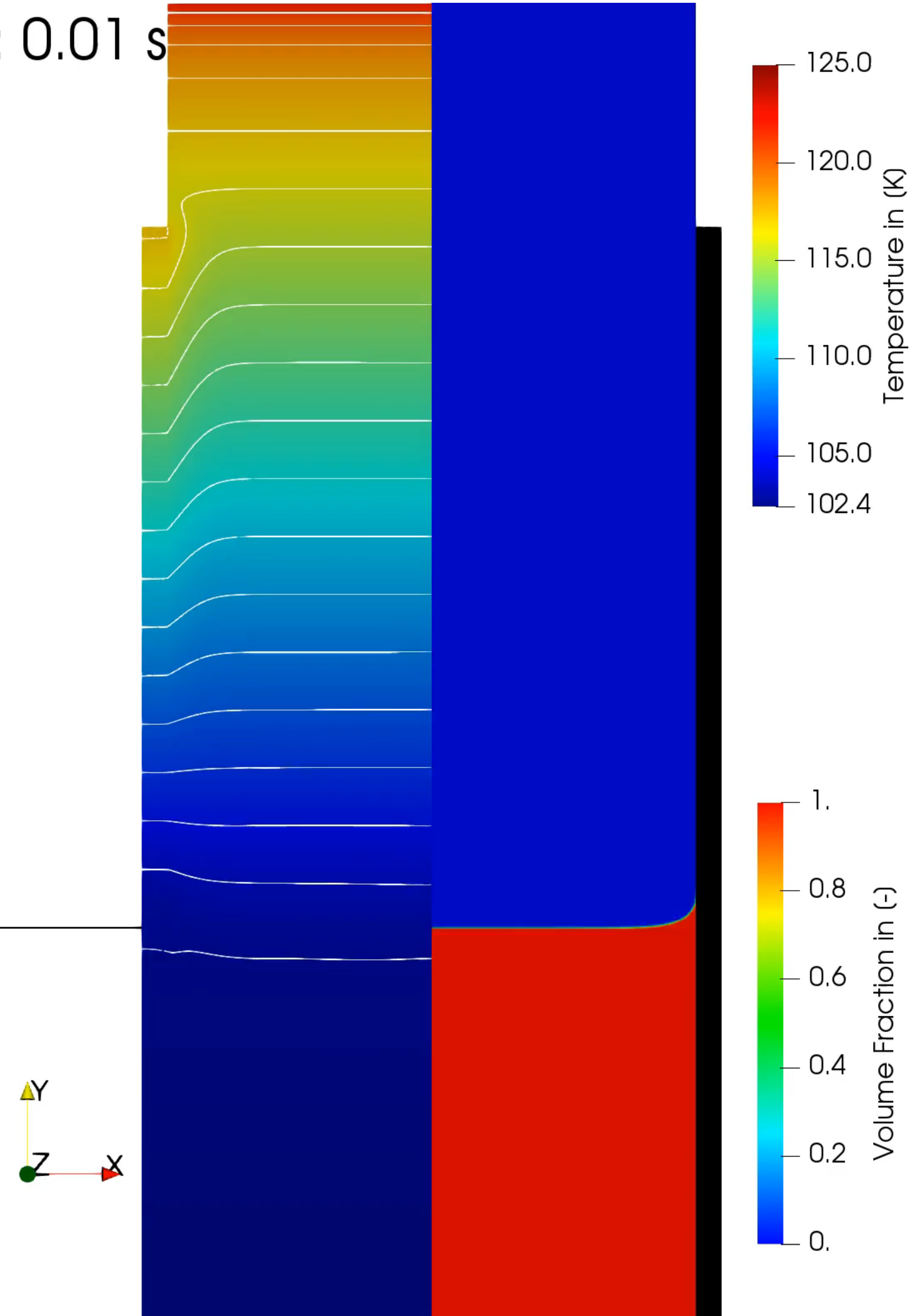
- Heat transfer from the wall to the fluid gets overestimated





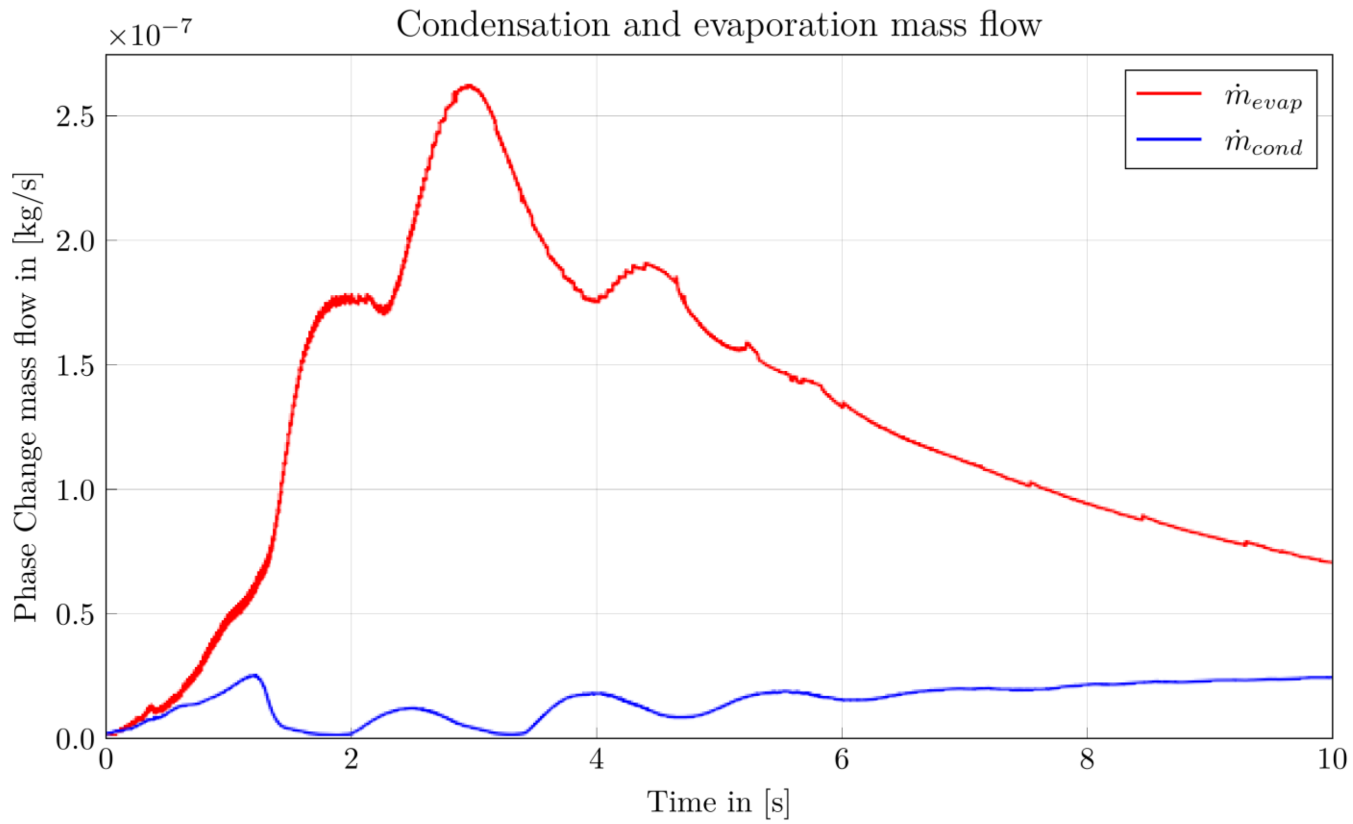
Numerical Results

- Condensation and evaporation occur
- Evaporation at wall
- Condensation in center
  - Rising pressure subcools bulk



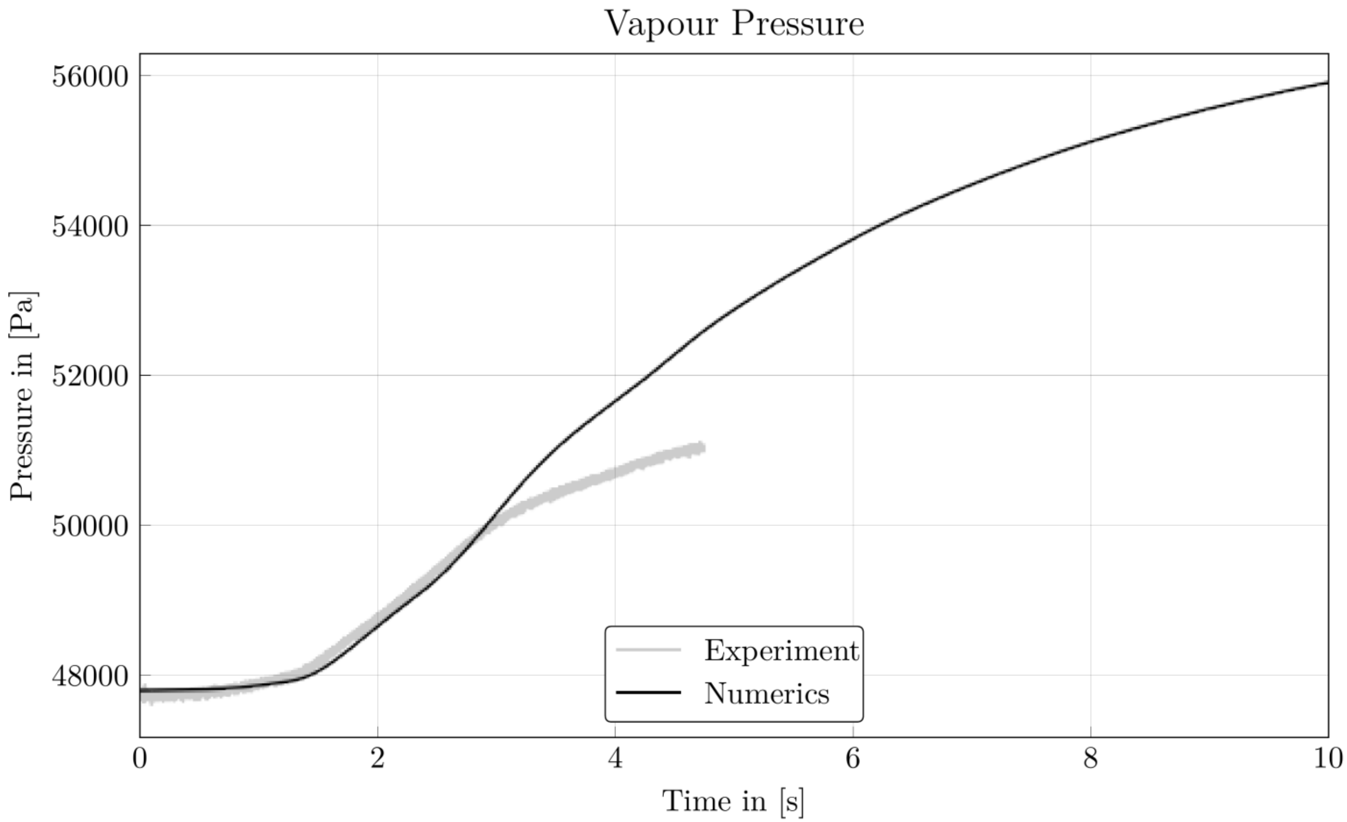
Numerical Results

- Evaporation outweighs condensation



Numerical Results

- Pressure is overestimated
- Evaporation likely overestimated



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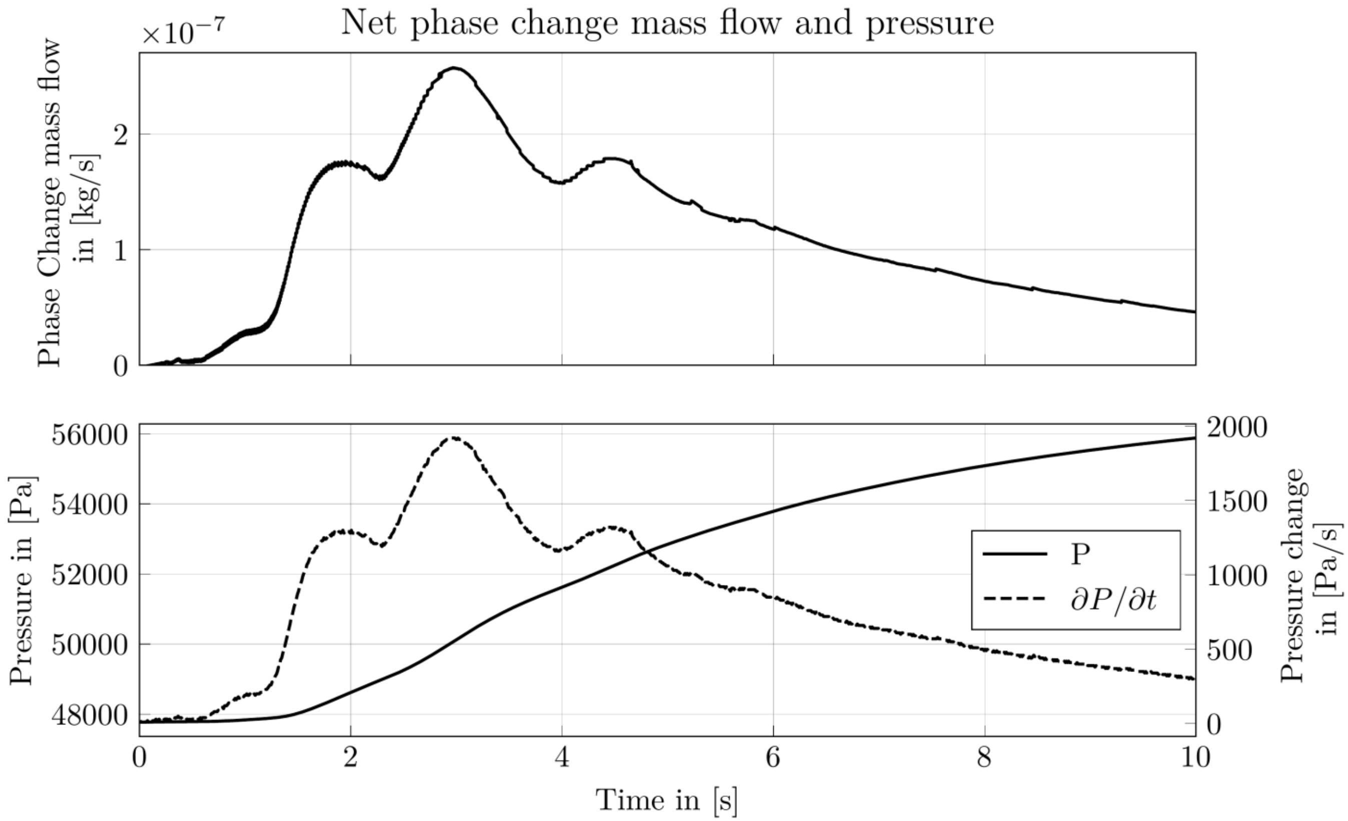
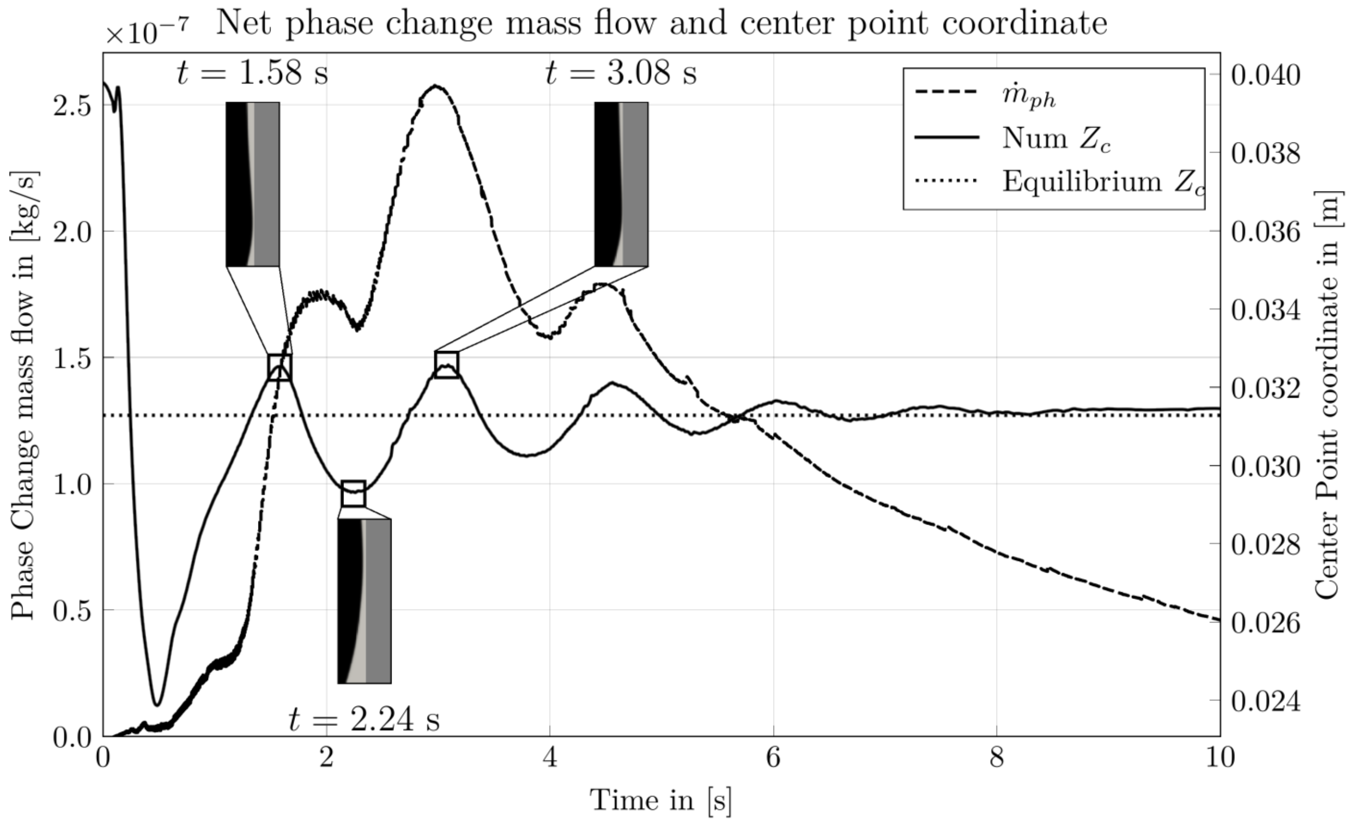
Numerical Results

- Phase change most significant influence on pressure



Numerical Results

- Interface position corresponds to phase change



Conclusion

- Observed phenomena could be reproduced
- Numerical data agrees with experimental data
- Interface position strongly linked to heat and mass transfer in liquid and vapour

Thank you for your attention!

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Numerical Tools – Governing Equations

- Conservation of mass:

$$\frac{\partial \alpha}{\partial t} + \frac{\partial \alpha u_j}{\partial x_j} = \frac{S_l}{\rho_l}$$

$$(1-\alpha)\frac{1}{\beta_2}\frac{\partial p}{\partial t} - (1-\alpha)\frac{\beta_1}{\beta_2}\frac{\partial T}{\partial t} + \frac{\partial \rho_v (1-\alpha)}{\partial t} + \frac{\partial \rho_v (1-\alpha) u_j}{\partial x_j} = S_v$$

- Conservation of momentum:

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = \mu \nabla^2 \mathbf{u} - \frac{\partial p}{\partial x_i} + \rho g_i + f_{\sigma,i}$$

- Conservation of energy:

$$\rho\left(\frac{\partial h}{\partial t} + u_j \frac{\partial h}{\partial x_j}\right) = -(\nabla \cdot \mathbf{q}) + \left(\frac{\partial p}{\partial t} + u_j \frac{\partial p}{\partial x_j}\right) + S_{pc}$$

Gradient based phase change model

Energy balance

$$\dot{m}h_{\text{lv}} = q_{\text{l}\rightarrow\text{int}} + q_{\text{v}\rightarrow\text{int}},$$

Heat fluxes

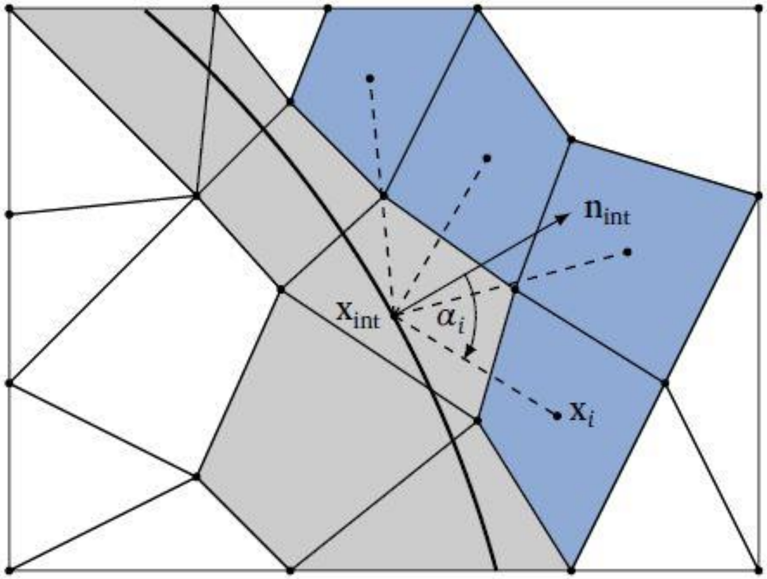
$$q_{\text{l}\rightarrow\text{int}} = k_{\text{l}}\nabla_{\text{int,l}}T$$

$$q_{\text{v}\rightarrow\text{int}} = k_{\text{v}}\nabla_{\text{int,v}}T$$

Temperature gradient (interface)

$$\nabla_{\text{int,l}}T = \sum_i w_i \frac{T_i - T_{\text{sat}}}{d_i}$$

$$w_i = \frac{\cos\alpha_i}{\sum_j \cos\alpha_j} \qquad \cos\alpha_i = \frac{(\mathbf{x}_i - \mathbf{x}_{\text{int}})\cdot\mathbf{n}_{\text{int}}}{\left|(\mathbf{x}_i - \mathbf{x}_{\text{int}})\right|}$$

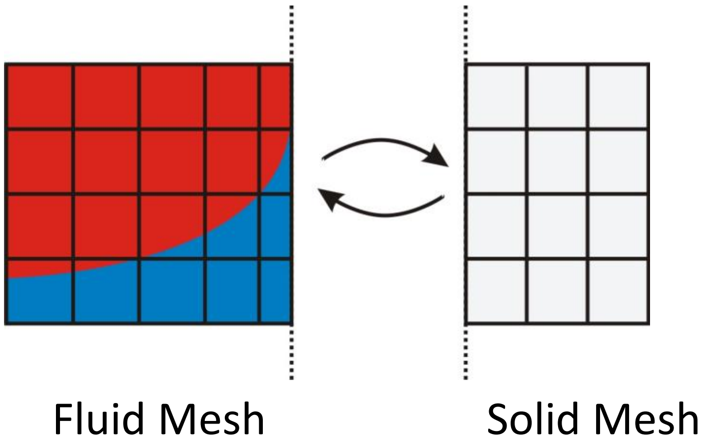


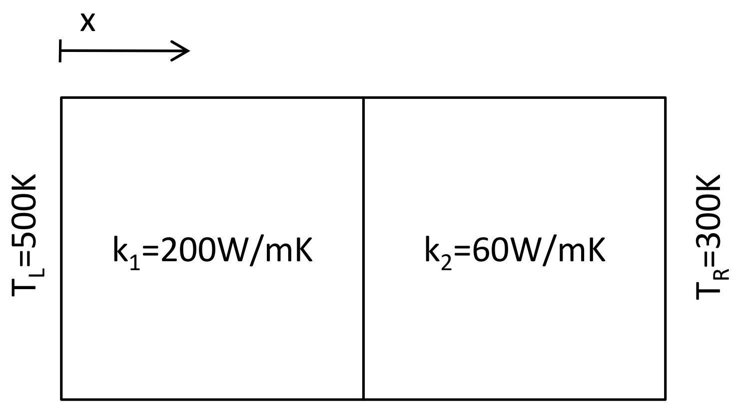
Interface temperature:

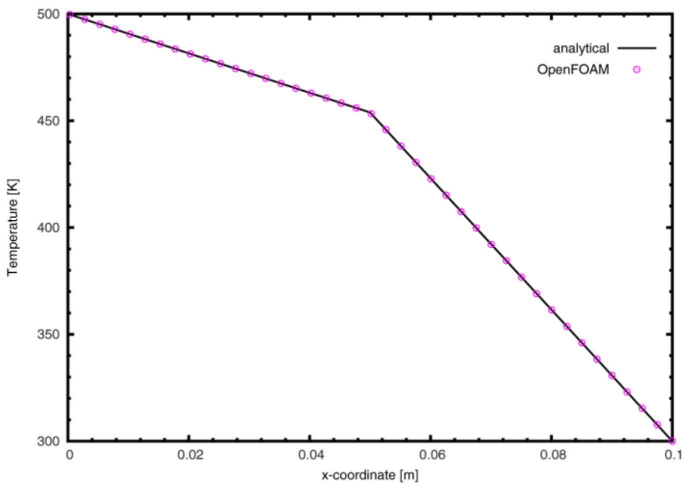
- dispersion force negligible
- influence of curvature on local sat. cond. negligible

$$\rightarrow\ T_{\text{int}} = T_{\text{sat}}(p_0)$$

Conjugate Heat Transfer: Validation







Dirichlet condition:

$$T_{Fluid} = T_{Solid}$$

Neumann condition:

$$k_{Fluid} \frac{\mathrm{d}T_{Fluid}}{\mathrm{d}x} = k_{Solid} \frac{\mathrm{d}T_{Solid}}{\mathrm{d}x}$$