Thermo-Structure Interaction in Rocket Nozzles

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Introduction

Project Goals

- Improved understanding of the complex problem of thermo-fluid-structure interaction (TFSI) for the design of future rocket nozzles
- Correct and precise prediction of mechanical and thermal loads acting on a rocket nozzle during flight conditions
- Development of a numerical model for TFSI [1] by coupling a complex turbulent flow model including shock-boundary-layer interaction using LES [2] with the fully coupled thermomechanical structure [3]

Objective

- Development of an overall 3D thermo-structure interaction (TSI) model enabling the realistic complete thermomechanical coupling
  →In contrast to most literature, consider all coupling terms in the balance equations for structure and thermo field
- Development of a robust, highly efficient monolithic solution approach for TSI based on block-Gauss Seidel preconditioning combined with algebraic multigrid

Thermo-Structure Interaction [3]

Weak Form of Volume Coupled Problem

$$\boldsymbol{r}_T = \int_{\Omega_0} \rho_0 \, C_{\mathrm{V}} \, \dot{T} \, \delta T \, \mathrm{d}V - \int_{\Omega_0} \boldsymbol{Q} \cdot \nabla_0 \delta T \, \mathrm{d}V - \int_{\Gamma_{0,\mathrm{N},T} \setminus \Gamma_{0,c}} \hat{Q} \, \delta T \, \mathrm{d}A - \int_{\Gamma_{0,c}} \hat{Q}_c \, \delta T \, \mathrm{d}A - \\ - \int_{\Omega_0} T \, m_0 \, \boldsymbol{I} : \dot{\boldsymbol{E}}^e \, \delta T \, \mathrm{d}V - \int_{\Omega_0} \mathcal{D}_{\mathrm{mech}} \, \delta T \, \mathrm{d}V = 0$$

$$\boldsymbol{r}_d = \int_{\Omega_0} \rho_0 \, \ddot{\boldsymbol{d}} \cdot \delta \boldsymbol{d} \, \mathrm{d}V + \int_{\Omega_0} \boldsymbol{S} \cdot \delta \boldsymbol{E} \, \mathrm{d}V - \int_{\Omega_0} \hat{\boldsymbol{b}}_0 \cdot \delta \boldsymbol{d} \, \mathrm{d}V - \int_{\Gamma_{0,\mathrm{N},d}} \hat{\boldsymbol{t}}_0 \cdot \delta \boldsymbol{d} \, \mathrm{d}V = \boldsymbol{0}$$

with $\mathcal{D}_{\mathrm{mech}} = \boldsymbol{\tau} : \boldsymbol{d}^p + \boldsymbol{A}_k * \dot{\boldsymbol{\alpha}}_k \geq 0$ and $\hat{Q}_c \, \mathrm{d}A_0 = \int_{\Gamma_{P,c}} h \, (T - T_\infty) \, |\tilde{\boldsymbol{n}}| \, \mathrm{d}\xi^1 \, \mathrm{d}\xi^2$

Available time integration schemes for TSI: generalised-α, one-step-θ scheme

Partitioned TSI

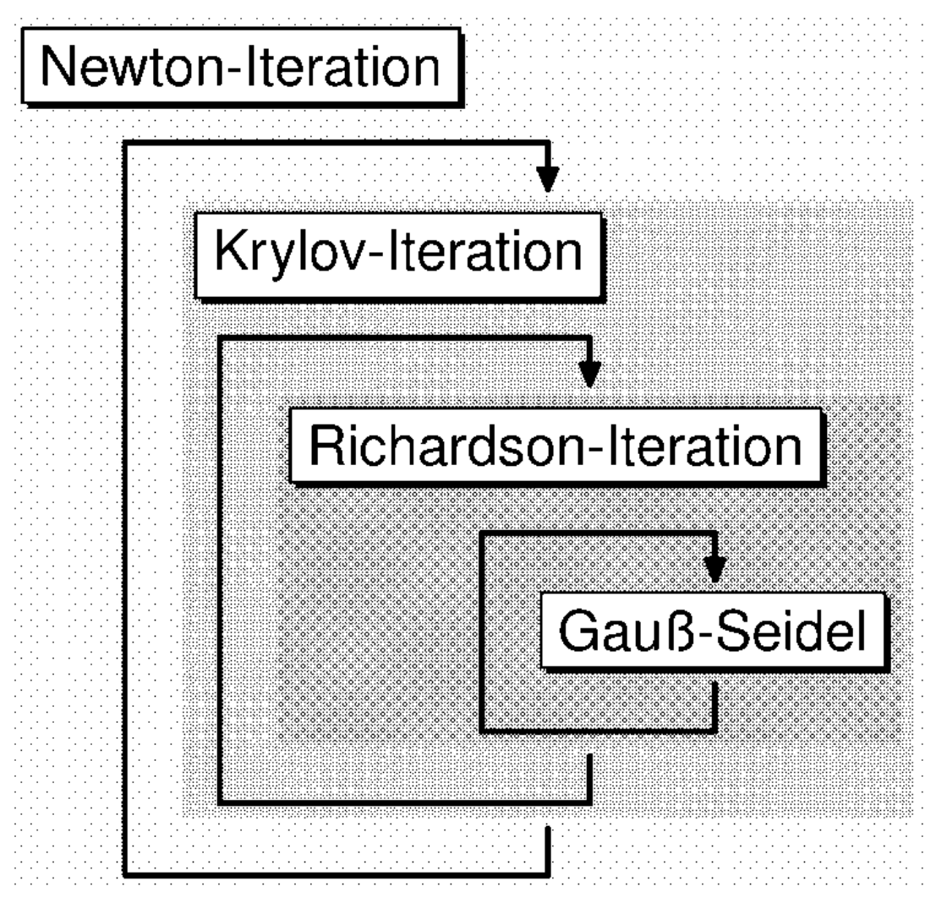
- Default in literature for solving TSI problem
- Individual fields may be treated by existing field-specific software packages
- Loosely and strongly coupled partitioned algorithms
  → Drawbacks: loosely: only conditional stable, strongly: slow convergence

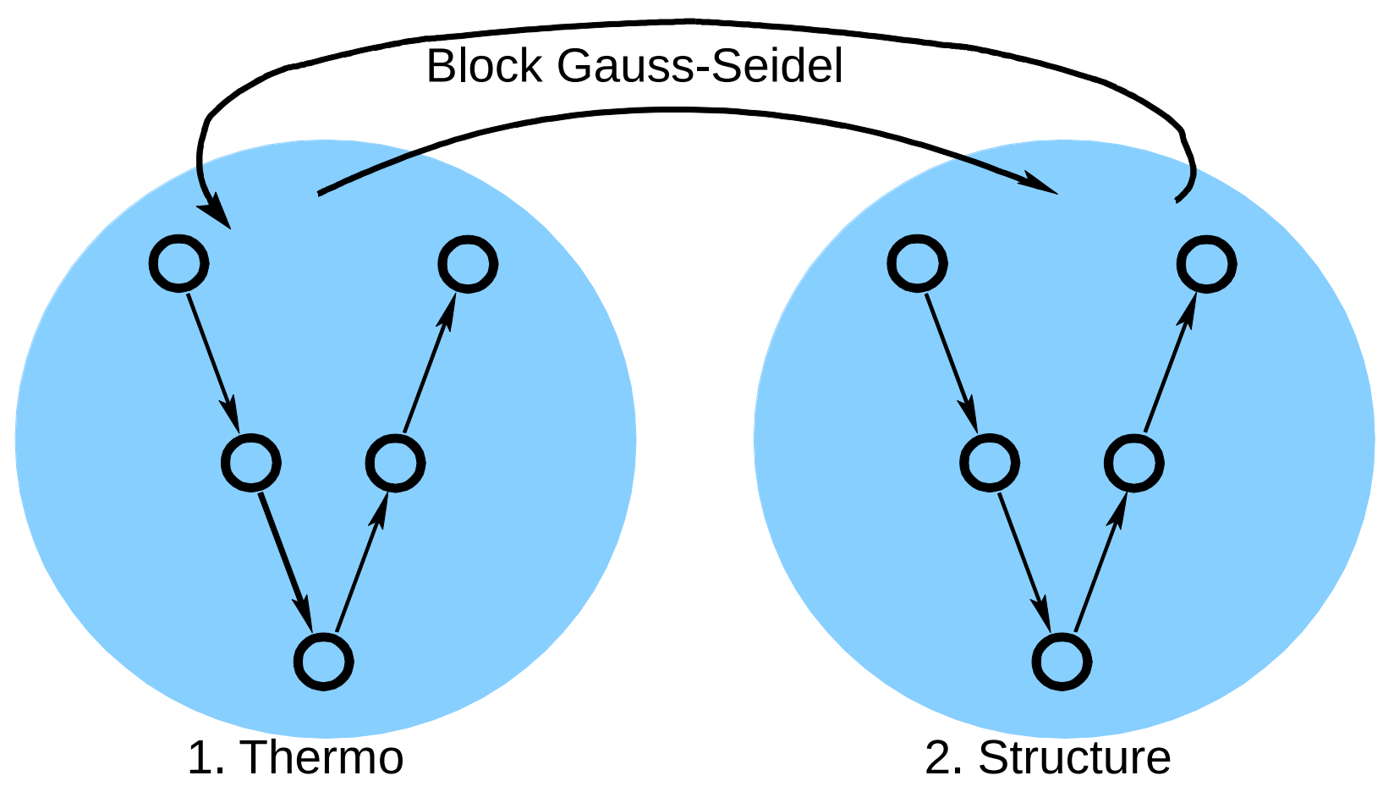
Monolithic TSI

- Solving of the coupled nonlinear system simultaneously

$$\begin{bmatrix} \boldsymbol{K}_{TT} & \boldsymbol{K}_{Td} \\ \boldsymbol{K}_{dT} & \boldsymbol{K}_{dd} \end{bmatrix}_{n+1}^{i} \begin{bmatrix} \Delta \boldsymbol{T} \\ \Delta \boldsymbol{d} \end{bmatrix}_{n+1}^{i+1} = - \begin{bmatrix} \boldsymbol{r}_T \\ \boldsymbol{r}_d \end{bmatrix}_{n+1}^{i}$$

- Exact fulfilment of coupling condition
- Good preconditioning strategy is required
- Robust, efficient solution strategy based on block-Gauss Seidel preconditioning combined with algebraic multigrid (AMG) for the approximation of diagonal blocks
- Large linear block system of equations





Materials for Thermo-Structure Interaction

Isotropic, linear Fourier's Law for the Heat Flux

$$\boldsymbol{Q} = -k_0 \, \boldsymbol{C}^{-1} \nabla_0 T$$

Thermomechanical Materials for the structure

- Different temperature-dependent materials available
- Additive split into mechanical and thermal parts

$$\boldsymbol{S} = \boldsymbol{S}(\boldsymbol{d}, T, \boldsymbol{\alpha}_k) = \boldsymbol{S}_d + \boldsymbol{S}_T$$

- Thermoelastic materials with temperature-dependent Young's modulus

$$\boldsymbol{S} = 2 \, \mu(T) \, \boldsymbol{E} + \lambda(T) \, (\boldsymbol{E} \cdot \mathbf{I}) \, \mathbf{I} + m(T) \, \Delta T \, \mathbf{I}$$

- Thermo-elasto-plastic materials
  - Small strain thermo-elasto-plastic material with von Mises plasticity including mixed hardening and temperature dependency [4]
  - Small strain Robinson's visco-plastic material [5]

Numerical Examples

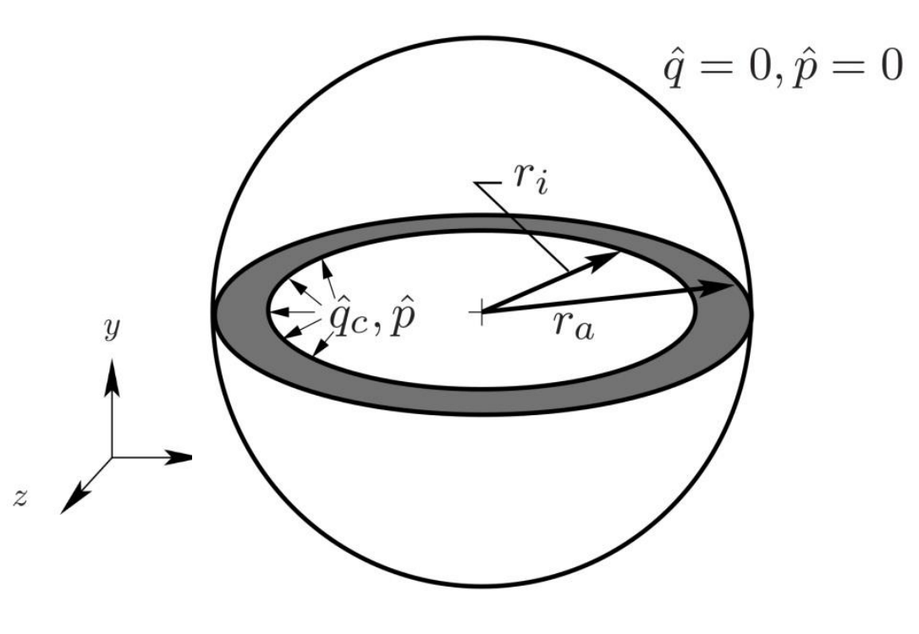
- Apply combined thermomechanical loading and one-step-θ time integration scheme

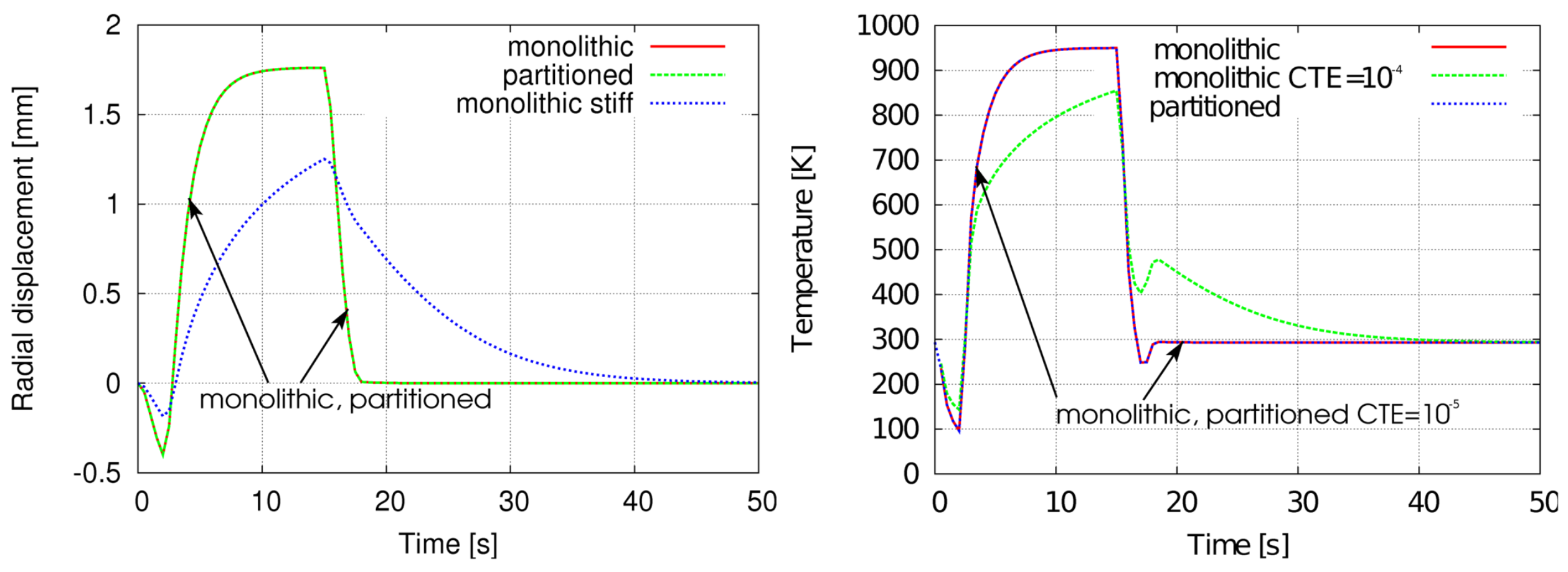
Material Parameters

	k $[\frac{\mathrm{W}}{\mathrm{m \cdot K}}]$	C_{V} $[\frac{\mathrm{J}}{\mathrm{kg \cdot K}}]$	α_T $[\frac{1}{\mathrm{K}}]$	T_0 [K]	E [GPa]	ν [-]	ρ $[\frac{\mathrm{kg}}{\mathrm{m}^3}]$
Copper alloy	310	373 s	$1.72 \cdot 10^{-5}$	293.15	$E = 148$	0.3	9130
Nickel jacket	75	444	$1.22 \cdot 10^{-5}$	293.15	193	0.3	8910

Internally loaded Hollow Sphere

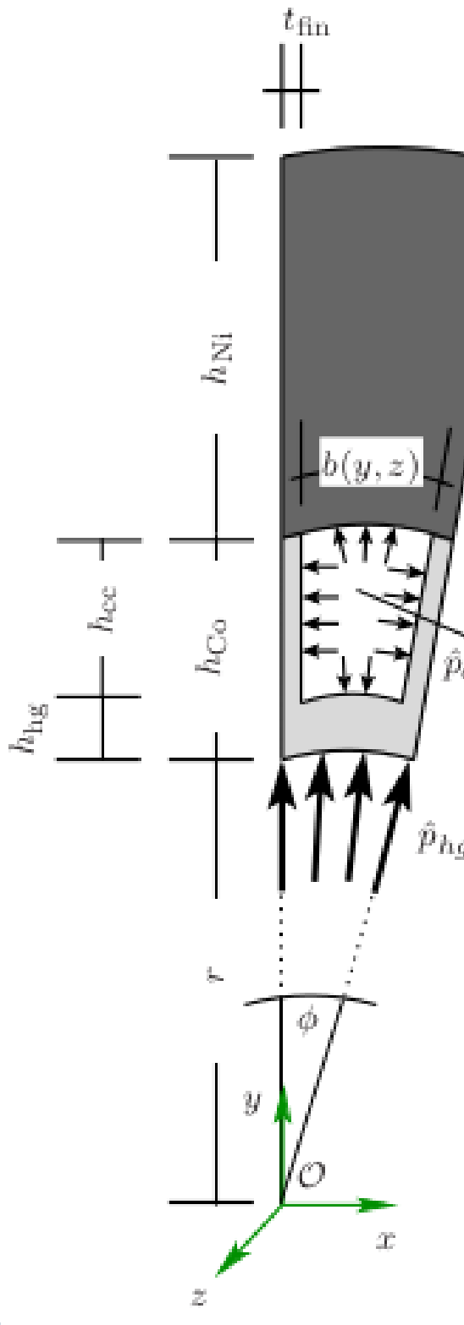
- Additional modified system with $\tilde{E} = 100E$ (left), and $\tilde{\alpha}_{\mathrm{T}} = 10\alpha_{\mathrm{T}}$ (right)

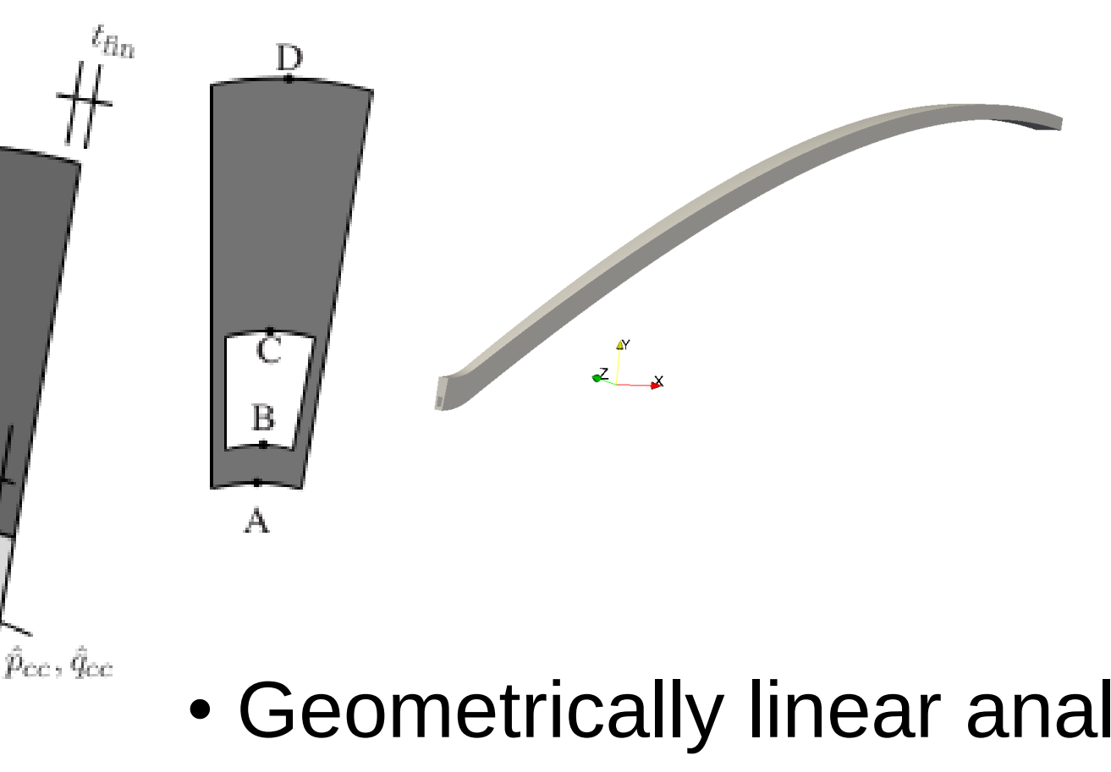




→ No convergence of partitioned TSI with full coupling and modified system
→ Solution times partitioned/monolithic TSI 434.2%

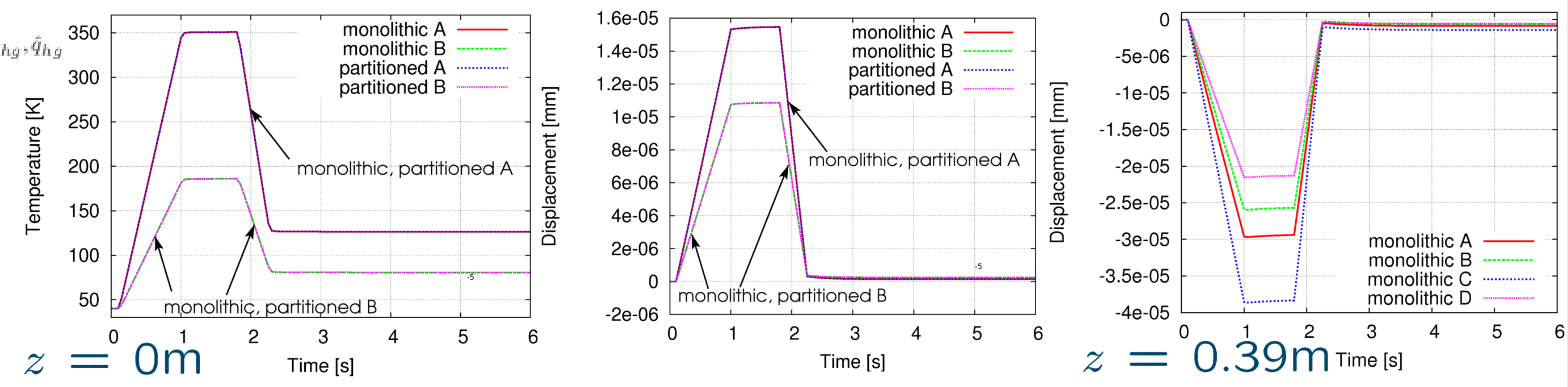
Fully 3D Rocket Configuration Including Cooling Channels





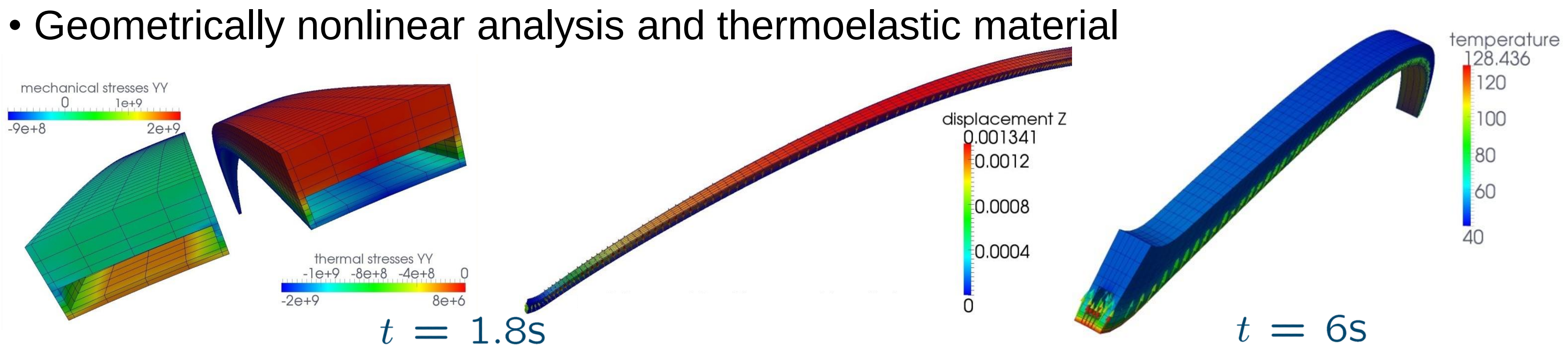
Phase	Time [s]	Pressure [MPa]		Temperature [K]	
		$\hat{p}_{hg}$	$\hat{p}_{cc}$	$T_{\infty,hg}$	$T_{\infty,cc}$
I	$0-0.1$	0	0	40	40
II	$0.1-1.0$	$0-10$	$0-2$	$40-950$	40
III	$1.0-1.8$	10	2.0	950	40
IV	$1.8-2.25$	$10-0$	$2-0$	$950-293.15$	40
V	$2.25-3.5$	0	0	293.15	40

- Geometrically linear analysis and thermoelastic material

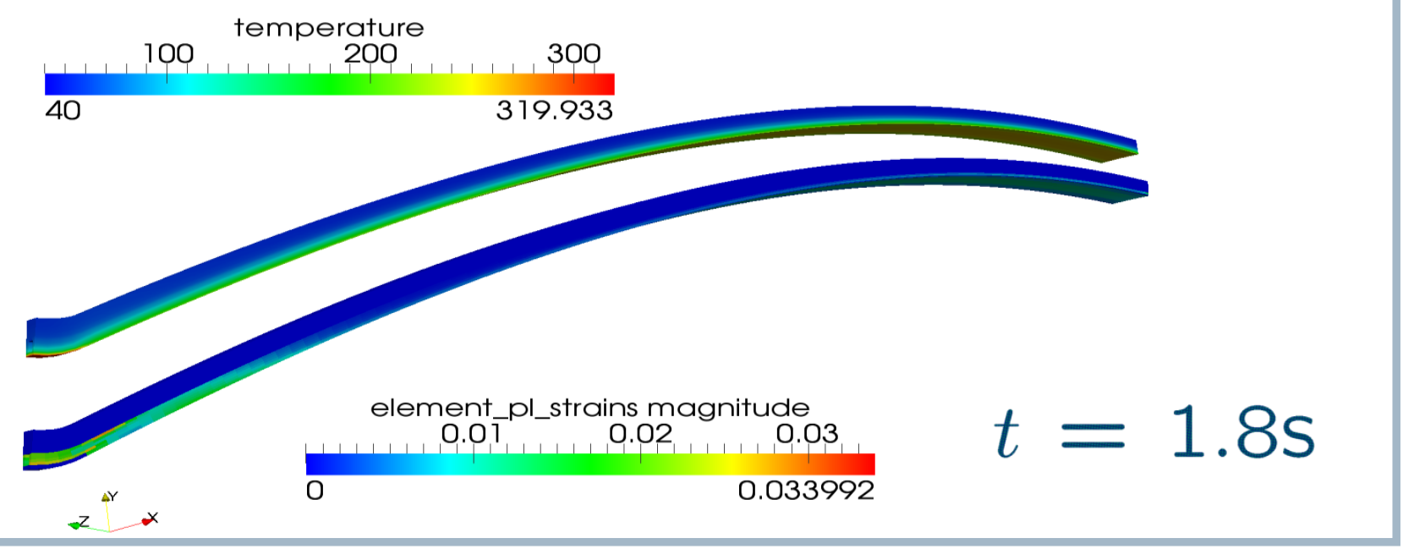


→ Solution times partitioned/monolithic TSI 141.25%

- Geometrically nonlinear analysis and thermoelastic material



- Geometrically nonlinear analysis and
  - Small strain thermo-elasto-plastic material for copper [4]
  - Thermoelastic material for nickel

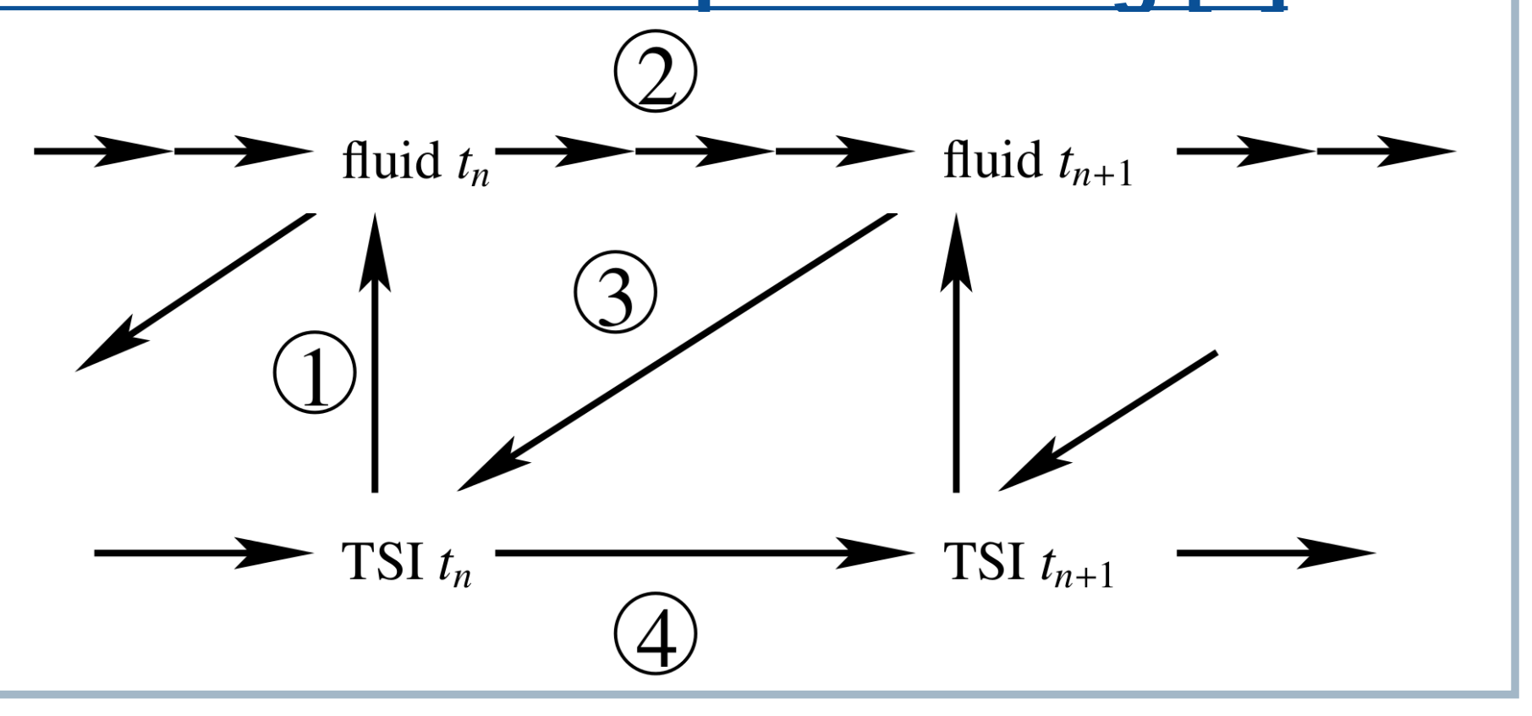


Partitioned TSI vs. Monolithic TSI

- Partitioned TSI only applicable for specific choice of material parameters
- Monolithic TSI applicable for the whole range of material parameters
- Partitioned TSI much slower, even if acceleration techniques are considered

Outlook – Thermo-Fluid-Structure Interaction

Loosely coupling of TFSI based on Dirichlet-Neumann partitioning [1]



Step 1: Dirichlet values of the solid are applied to the fluid
Step 2: Fluid is advanced in time (including subcycling)
Step 3: Neumann loads of the fluid are applied to the solid
Step 4: TSI system is advanced in time

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