Temperature Dependence of Material Properties and its Influence on the Thermal Distribution in Regeneratively Cooled Combustion Chamber Walls

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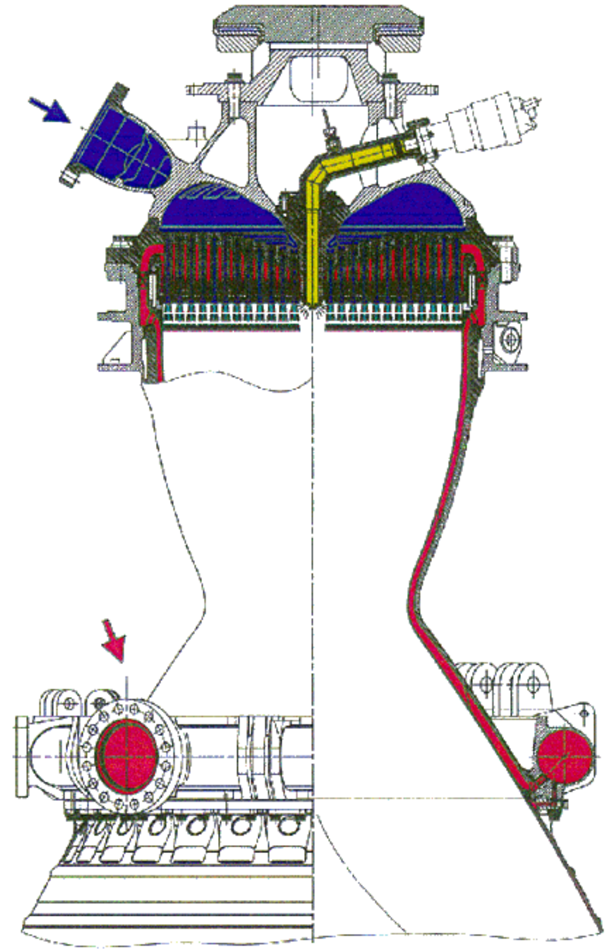
conditions in regeneratively cooled LOX/GH_2-engines

- hot gas temperature: ≈ 3500 K
- pressure: ≈ 11 MPa
- heat flux: up to 80 MW/m^2
- LH_2-temperature:
  - cooling channel inlet ≈ 40 K
  - cooling channel outlet ≈ 100 K
- wall structure temperature:
  - hot gas side ≈ 400 - 800 K
  - cooling fluid side ≈ 40 - 100 K



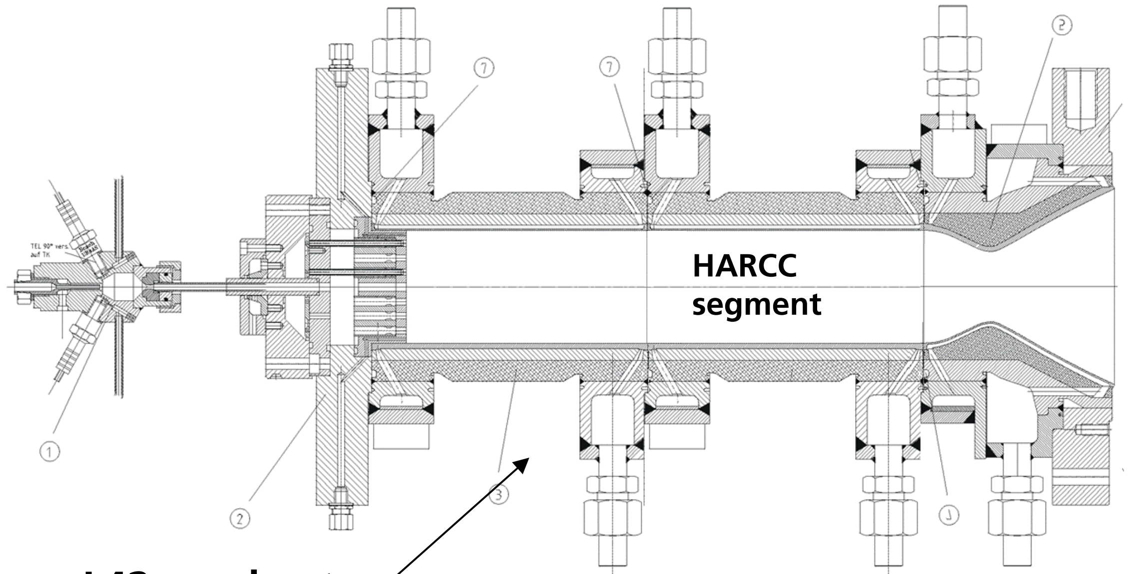
hot gas wall temperature: ΔT=40 K ≈ 50% life time

A. Fröhlich, M. Popp, G. Schmidt, D. Thelemann. Heat Transfer Characteristics of H_2/O_2 Combustion Chambers, AIAA 93-1826, 29th Joint Propulsion Conference, Monterey, CA, 1993

stratification in cooling channels with high aspect ratio

HARCC-experiment

- P8 test bench
- LH_2-cooled L42 combustor
- pressures up to P_C = 9 MPa
- heat fluxes up to 40 MW/m^2
- variation of AR=1.7 ... 30



L42-combustor

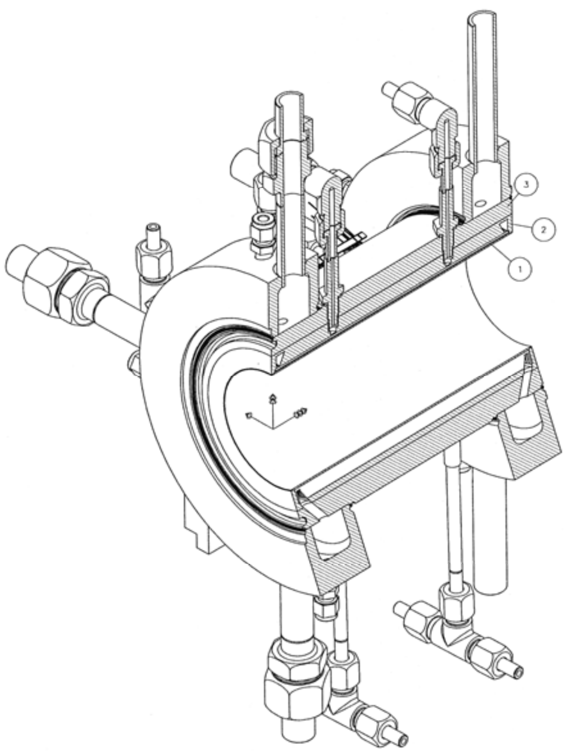
P8 test bench

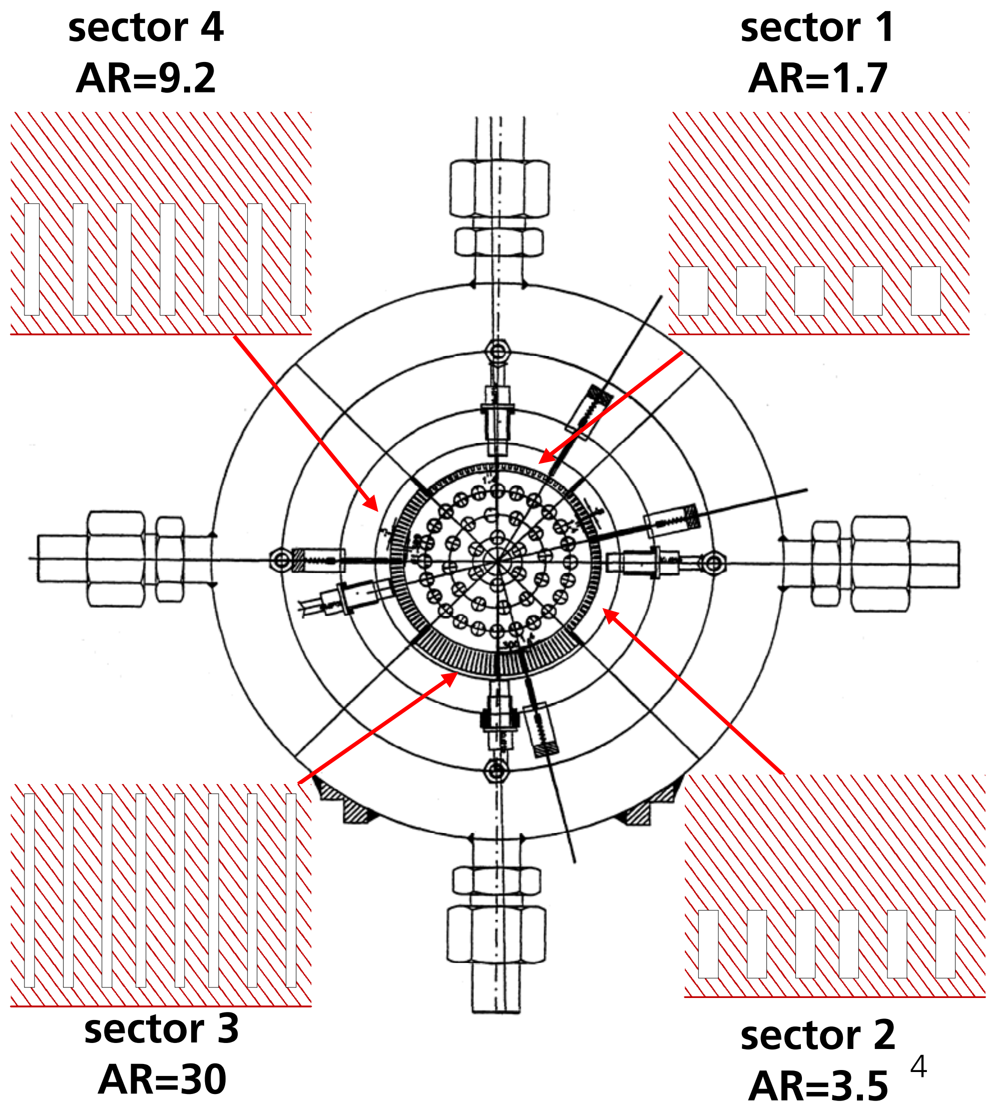
D. Suslov, A. Woschnak, J. Sender, M. Oschwald, Test specimen design and measurement technique for investigation of heat transfer processes in cooling channels of rocket engines under real thermal conditions, AIAA 2003-4613, 39th Joint Propulsion Conference, Huntsville, 2003

A. Woschnak, D. Suslov, M. Oschwald, Experimental and Numerical Investigations of Thermal Stratification Effects, AIAA 2003-4615, 39th Joint Propulsion Conference. Huntsville, 2003

HARCC geometries

sector no.	width [mm]	height [mm]	aspect ratio	fin width [mm]
1	1.2	2.0	1.7	1.4
2	0.8	2.8	3.5	1.4
3	0.3	9.0	30	1.4
4	0.5	4.6	9.2	1.4

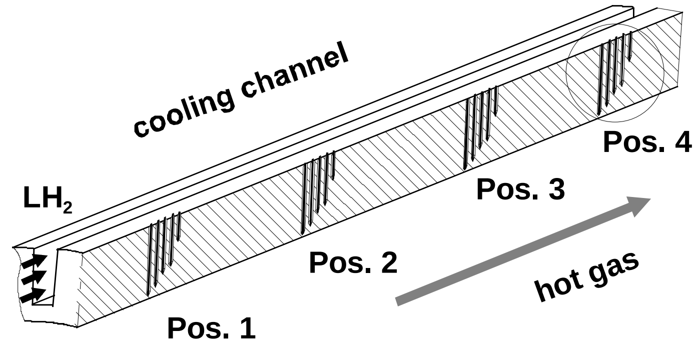


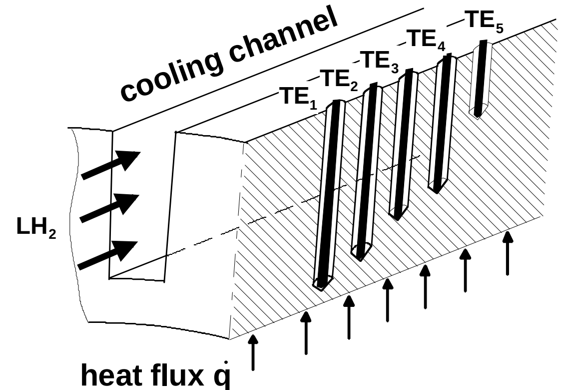


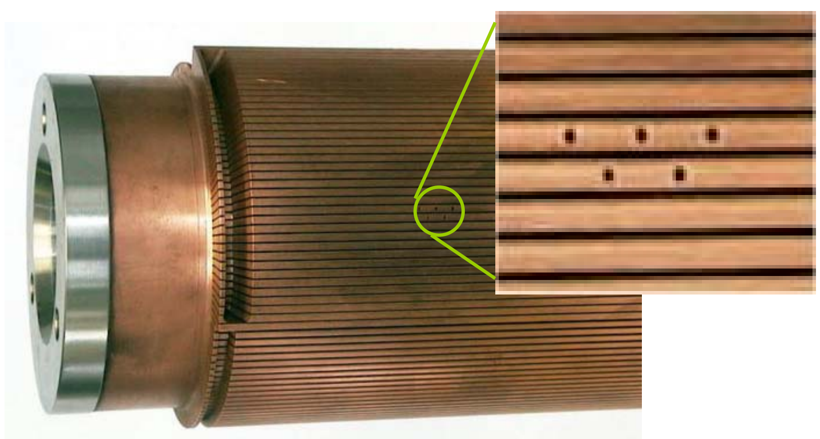
DLR

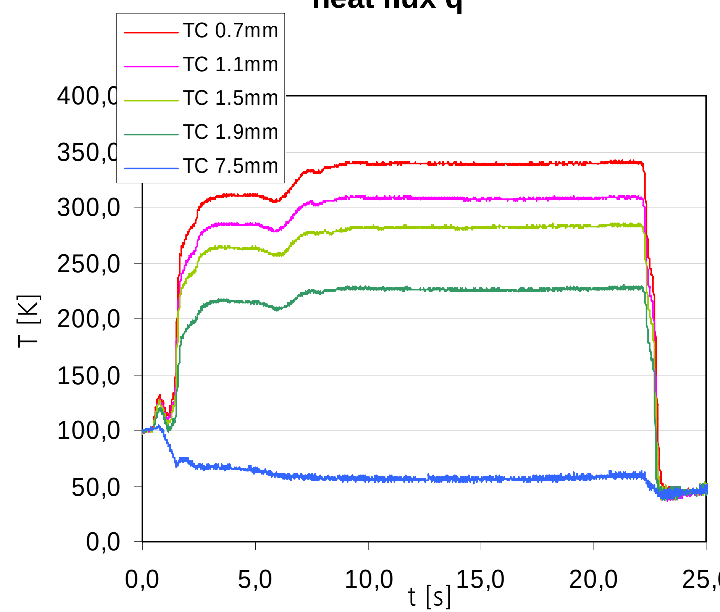
temperature determination in wall structure with thermocouples

- **measurements at 4 axial locations**
  - z=52mm, 85mm, 119mm, 152mm downstream duct entrance
- **5 radial positions**
  - 0.7mm, 1.1mm, 1.5mm, 1.9mm, 7.5mm from hot gas side
- **determination of surface temperature, heat flux and heat transfer coefficients by inverse method**









heat conduction / material properties

instationary problem:

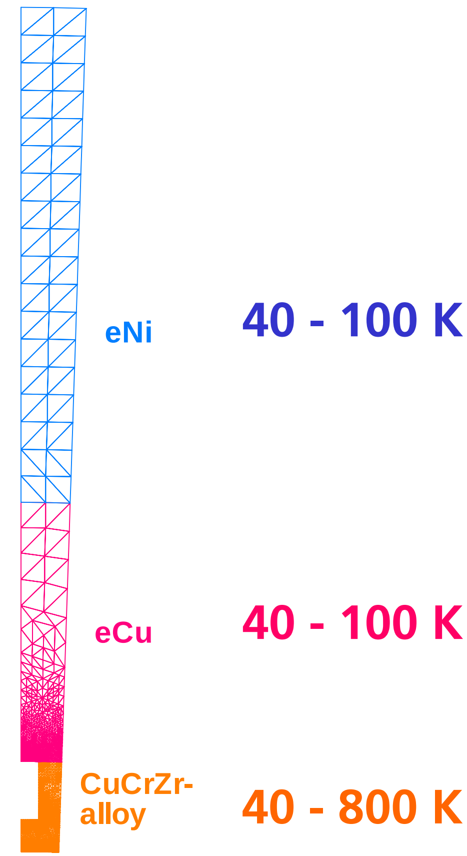
$$\rho \frac{\partial (c_V T)}{\partial t} - \nabla \cdot (\lambda \nabla T) = 0$$

stationary problem:

$$-\nabla \cdot (\lambda \nabla T) = 0$$

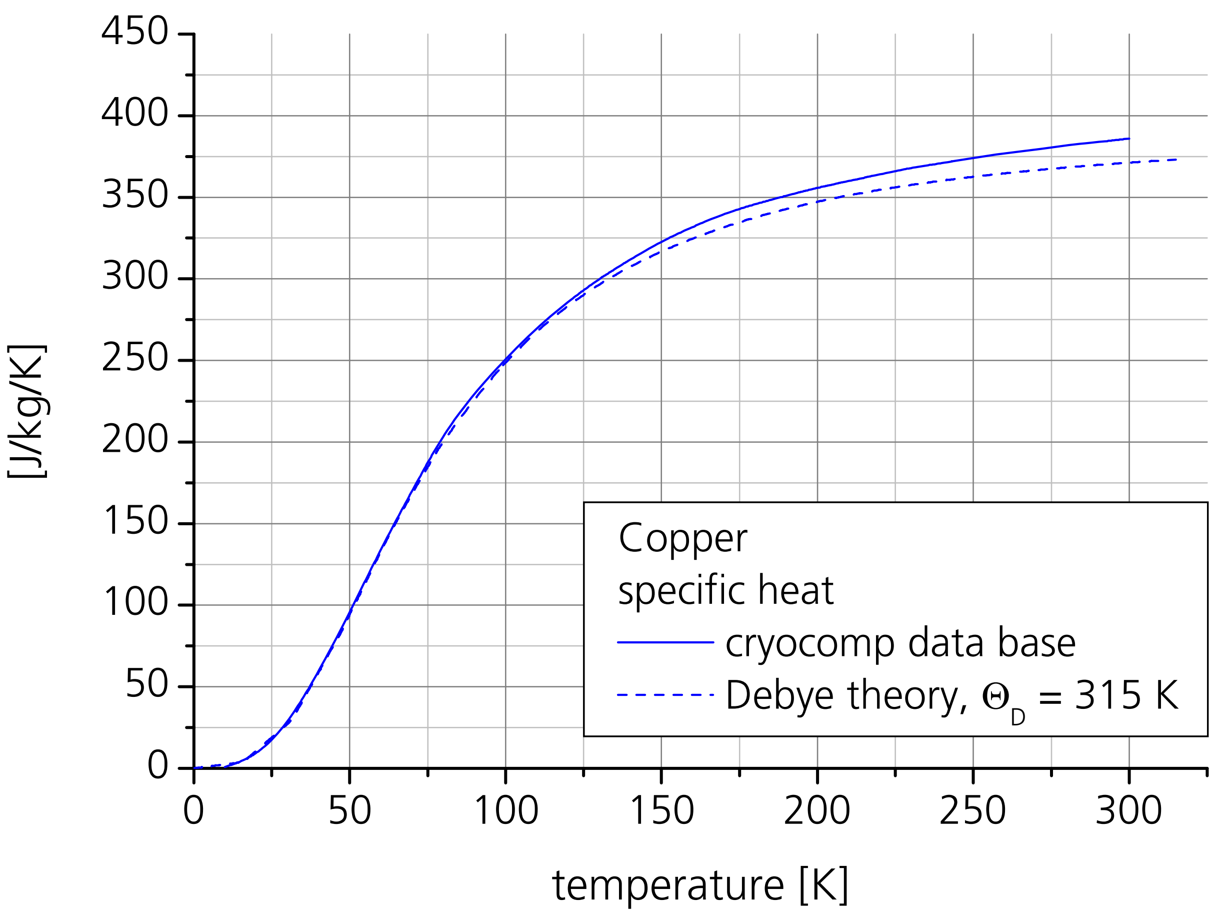
specific heat: $c_V \approx$ **25.9 J/mol/K**
(Dulong-Petit, ambient temperature)

heat conductivity: $\lambda \approx$ **350 W/Km**
(typical Cu-alloy)



combustion chamber wall construction

Debye-theory of the specific heat



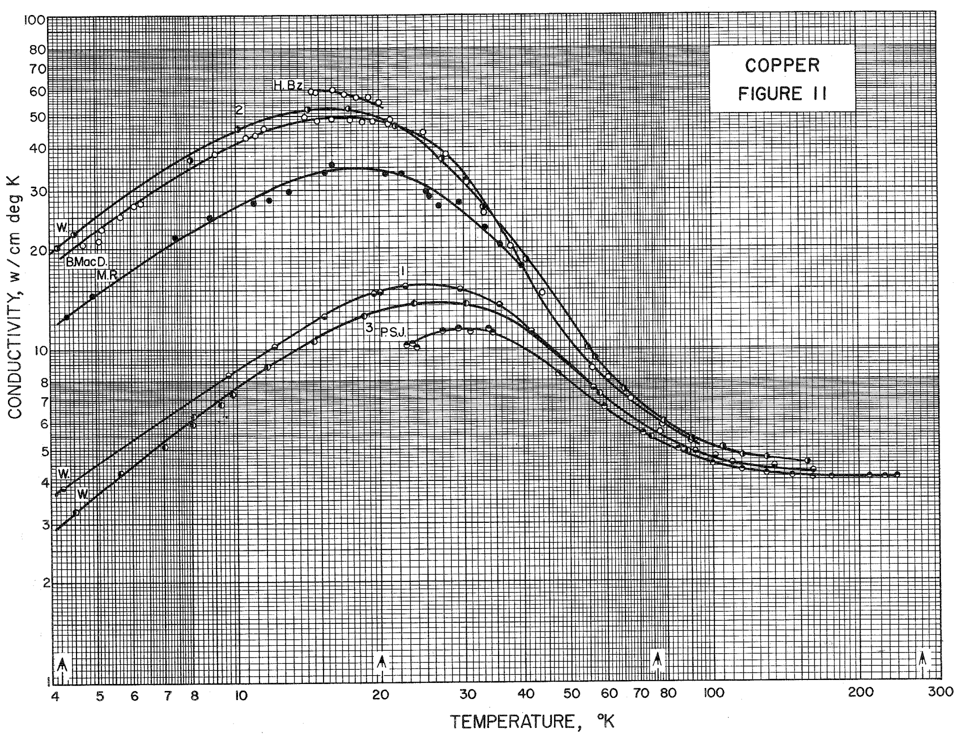
Debey-theory

- **quantum mechanics for low temperature behaviour**
- **high temperature limit:**

  c_V **= 3R** (Dulong-Petit)
- **low temperature limit:**

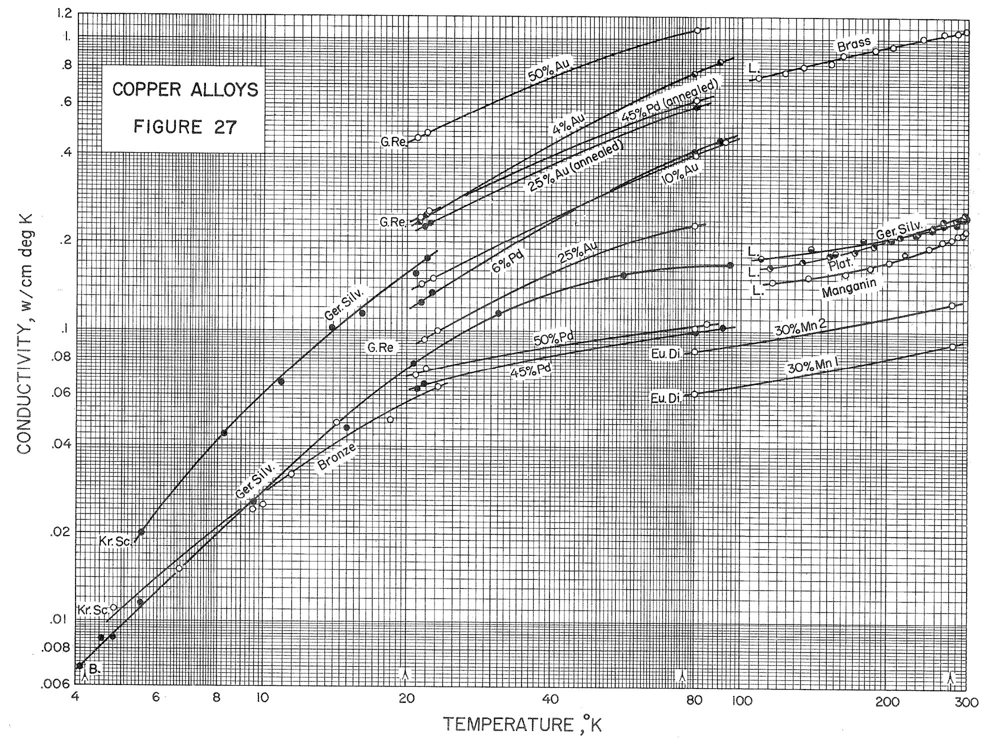
  $c_V \propto a \cdot (T/\Theta_D)^3$
- **for copper:** $\Theta_D \approx$ **315 K**

thermal conductivity at low temperatures



pure copper

maximum near 20 K



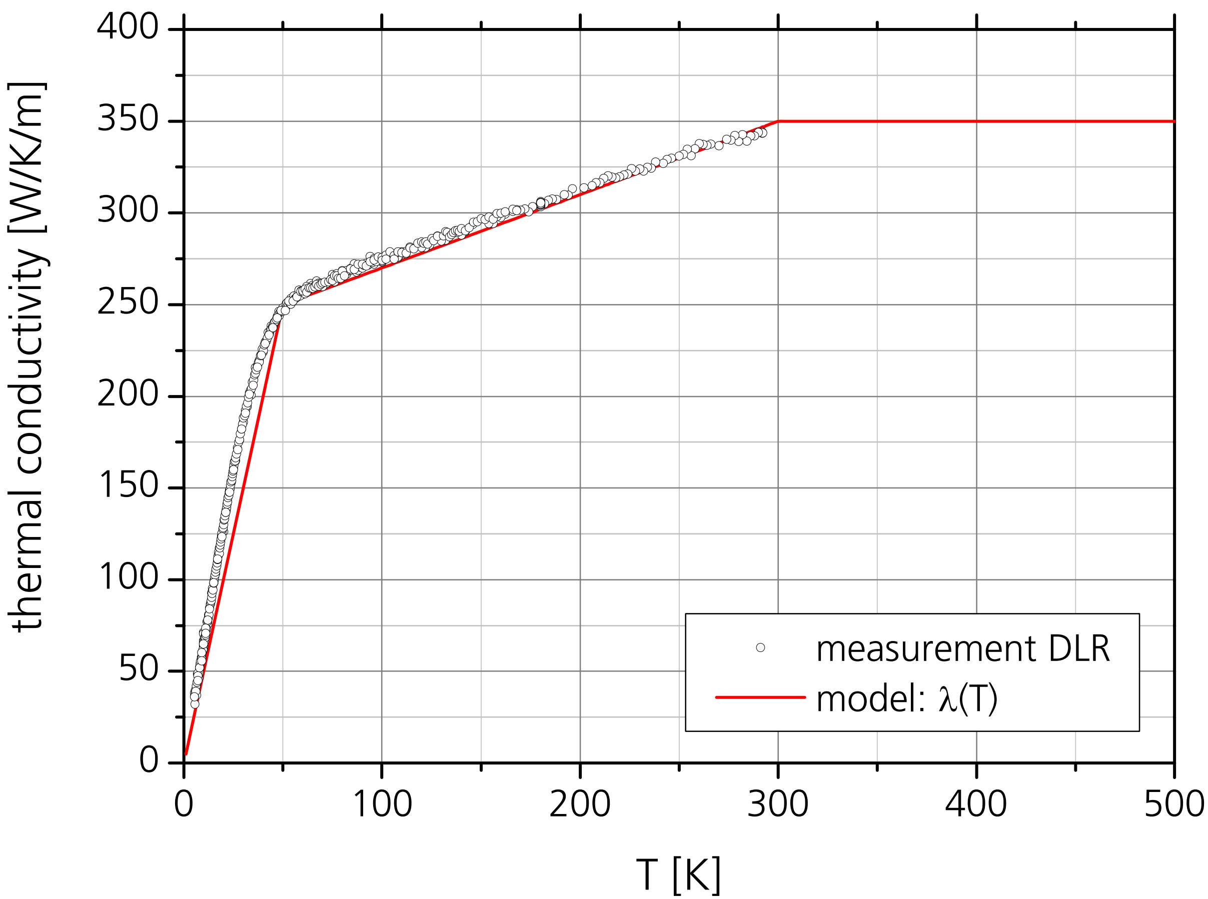
copper alloys

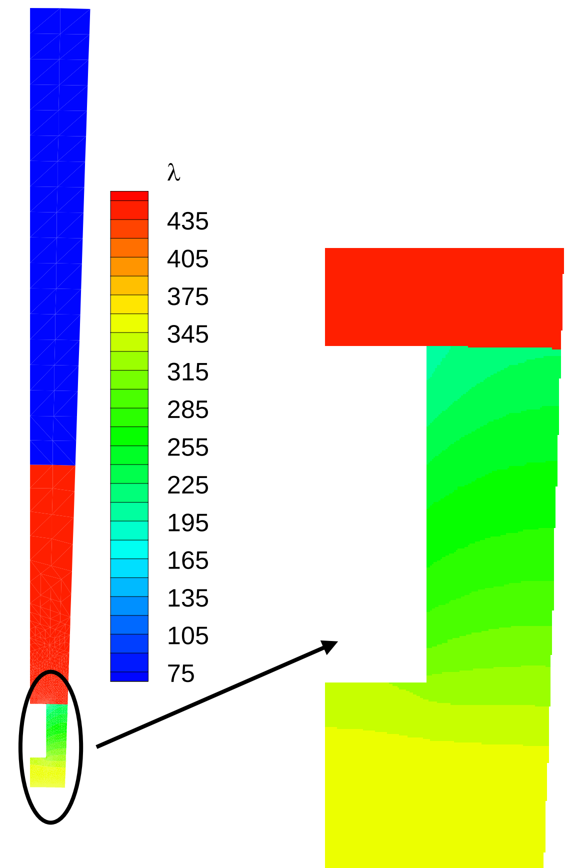
phonon scattering at lattice imperfections:

reduction of thermal conductivity

R.L. Powell and W. A. Blanpied, Thermal Conductivity of Metals and Alloys at Low Temperature, NBS Circular 556, 1954

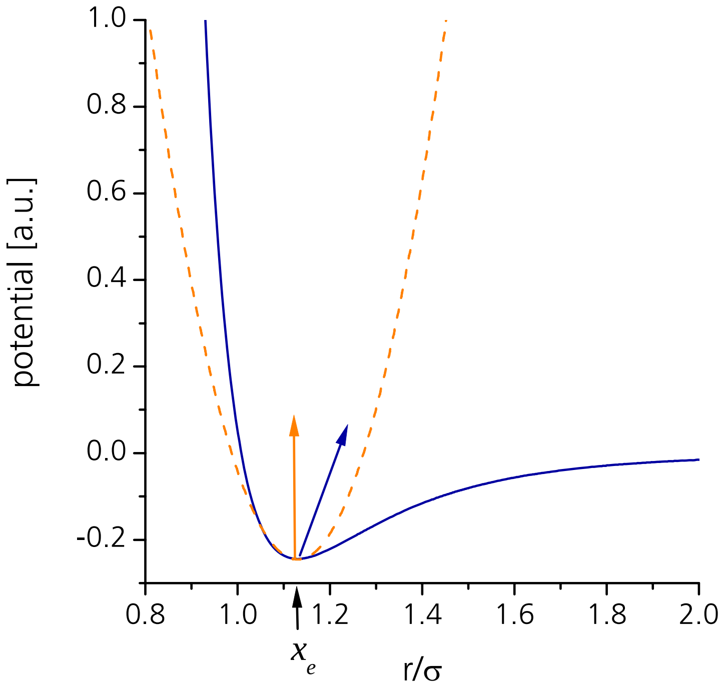
thermal conductivity of copper alloy for L42-combustor





variation of thermal conductivity in wall with thermal field

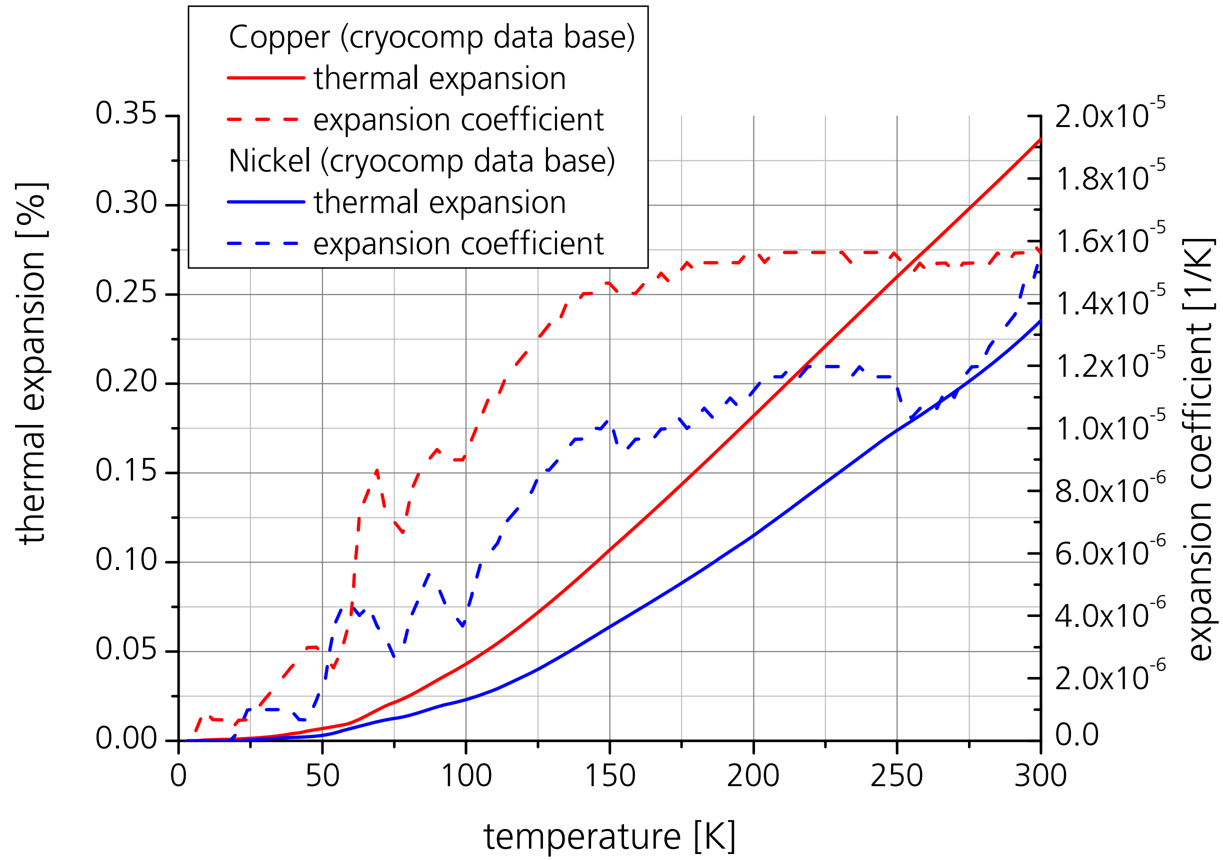
thermal expansion coefficient



$$U(x) = cx^2 - gx^3 + \ldots$$

$$\langle x \rangle = x_e + \frac{3g}{4c^2} k_B T$$

$$\alpha = \frac{1}{\langle x \rangle} \frac{d\langle x \rangle}{dT}$$



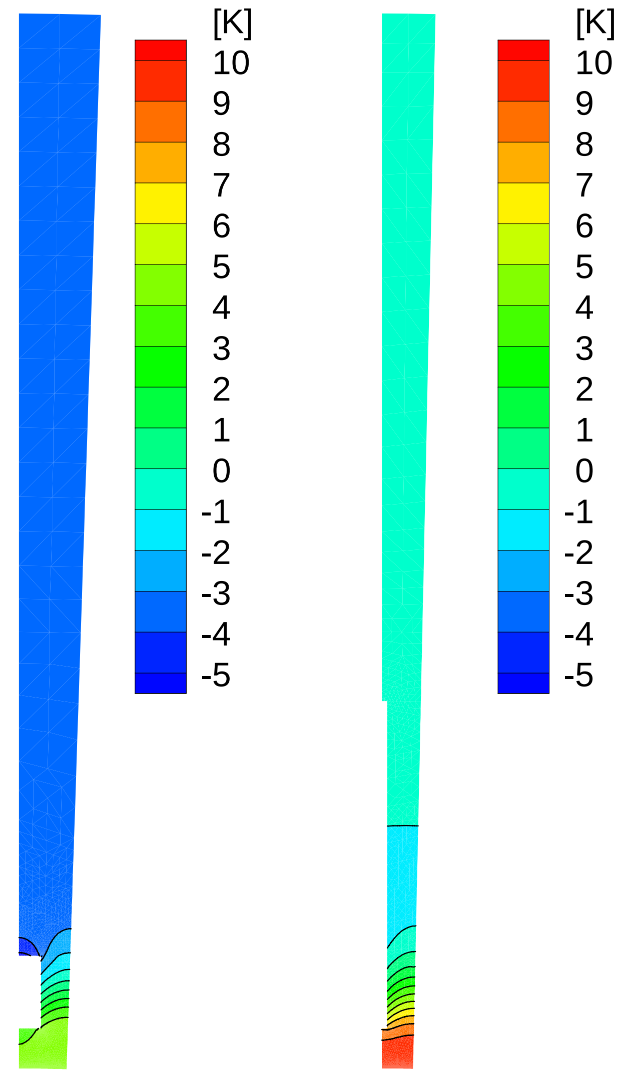
- thermal expansion due to anharmonicity of potential
- expansion coefficient vanishes at T=0

thermal field w/o and with temperature dependence of λ

- HARCC experiment, 52 mm downstream cooling fluid inlet

AR H/B	sector	T_{H2}	T_W [K]		ΔT_W [K]
			T_c λ=const.	T_v λ(T)	
1.7	Q1	85	380.9	385.0	4.9
3.5	Q2	90	363.3	369.4	6.1
9.1	Q4	95	349.9	358.2	8.3
30	Q3	100	343.6	352.7	9.1

$\Delta T_W = T_v - T_c$



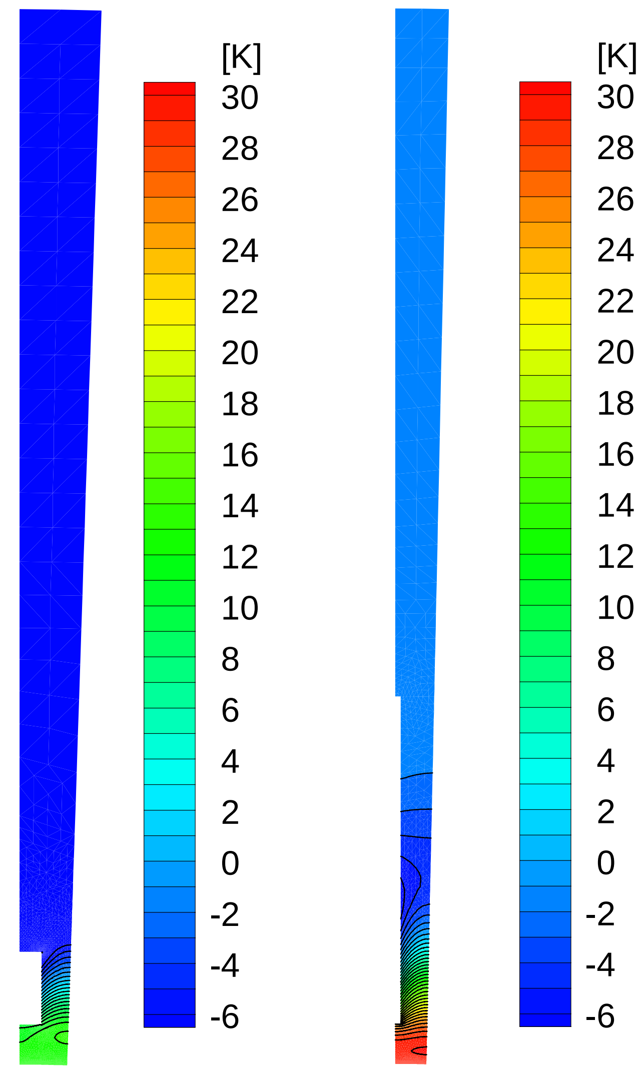
H/B=1.7 H/B=30

thermal field w/o and with temperature dependence of λ

- cooling fluid temperature: 50K

AR H/B	sector	T_W [K]		ΔT_W [K]
		T_c λ=const.	T_v λ(T)	
1.7	Q1	349.0	361.3	12.3
3.5	Q2	326.6	345.7	19.1
9.1	Q4	308.3	334.6	26.3
30	Q3	297.3	327.0	29.7

$\Delta T_W = T_v - T_c$

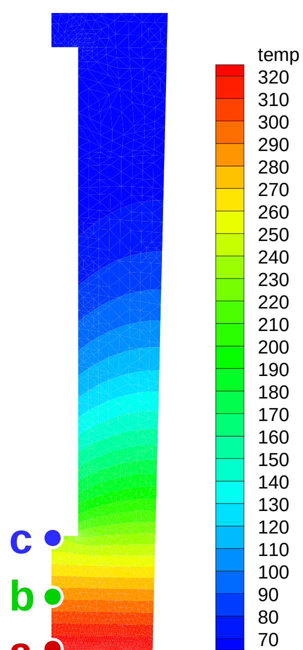


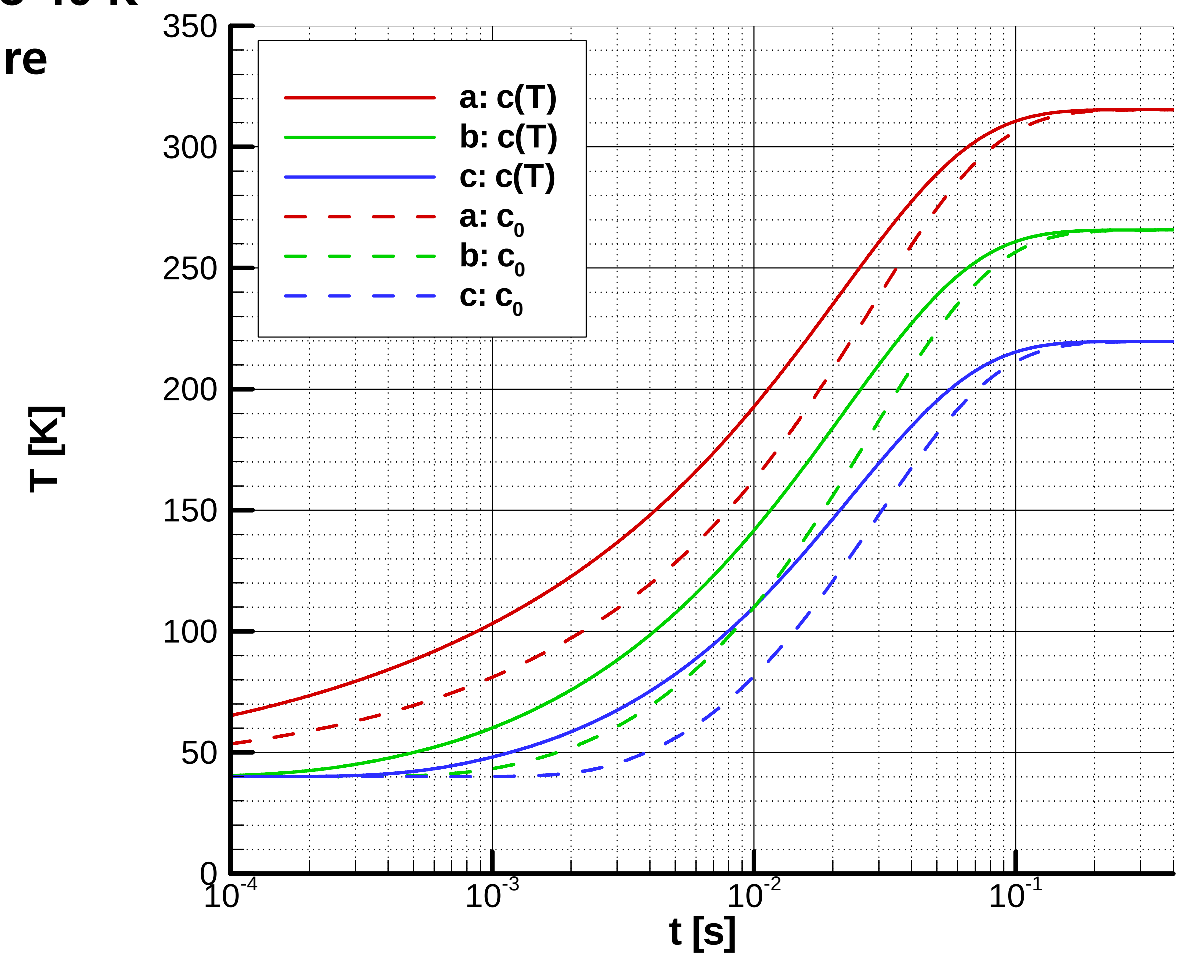
H/B=1.7 H/B=30

transient thermal field: $c_v=c_0$ vs. $c_v=c_v$ (T)

wall temperatures

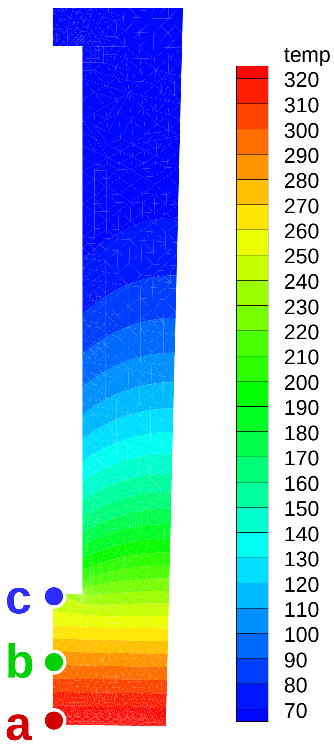
- pre-cooling of structure to 40 K
- instantaneous temperature increase at t=0

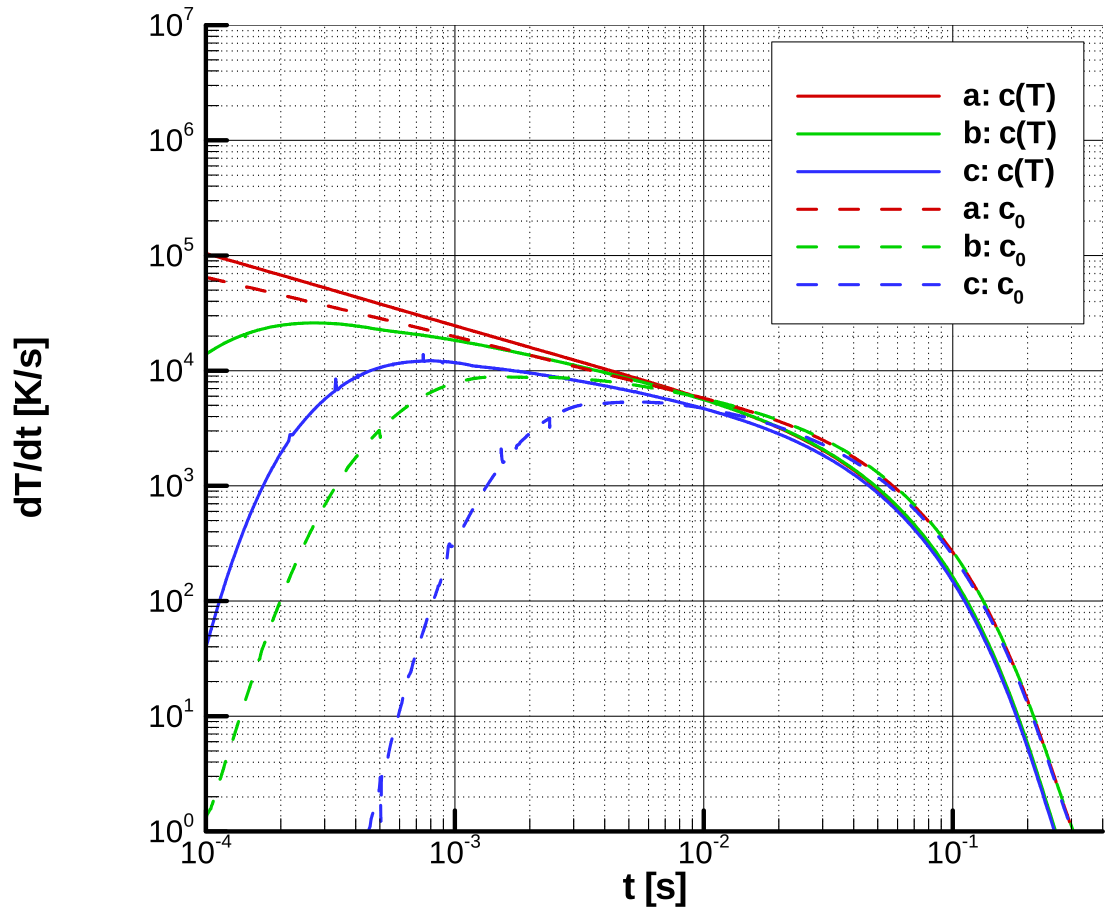




transient thermal field: $c_v=c_0$ vs. $c_v=c_v\,(T)$

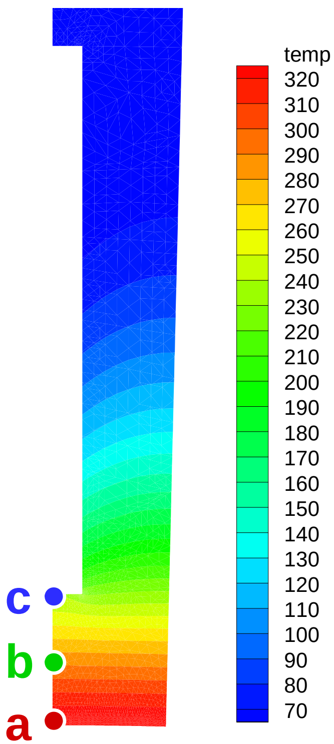
temporal gradients

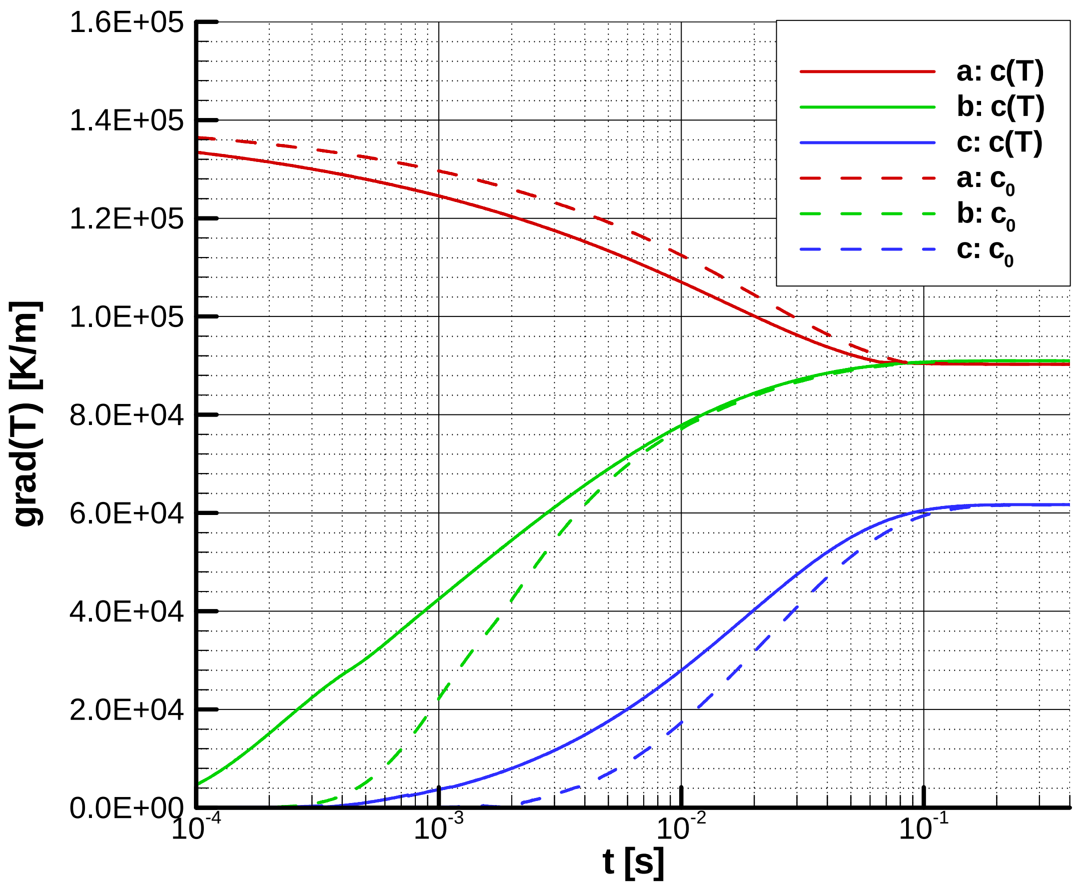




transient thermal field: c_v=c_0 vs. c_v=c_v (T)

spatial gradients





summary

specific heat c_V
thermal conductivity λ
thermal expansion coefficient α

- show significant temperature dependence
- c_V, λ, α disappear at absolute zero

$\alpha \rightarrow 0$ for $T \rightarrow 0$

- reduced thermal stress at low temperature

$c_V \rightarrow 0$ für $T \rightarrow 0$

- only minor differences as compared with simulation results with c_V=const.

$\lambda \rightarrow 0$ for $T \rightarrow 0$

- increase of hot gas side wall temperature
- relevant level of increase at low cooling fluid temperature and high AR