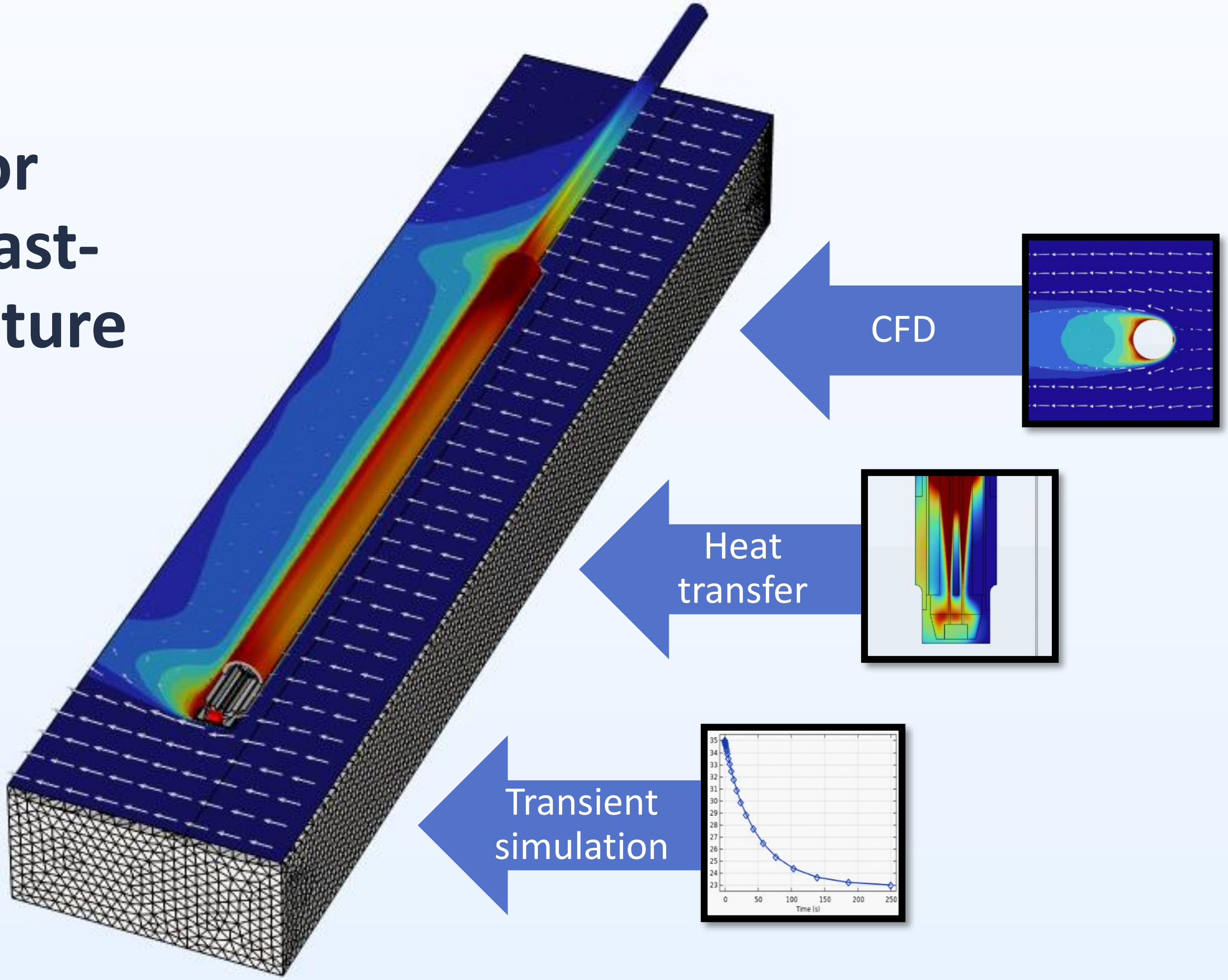
FEM-modelling for concept design of fast-responding temperature probes



19. September 2024 | Seeon

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Global Development Research & Testing

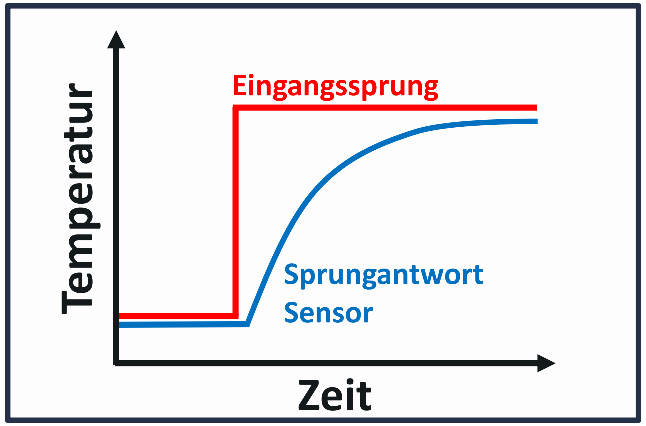
Agenda

1. Introduction
2. Setup model
3. Simulation A: Validation „basic setup“
4. Simulation B: Variation of measuring scenario (contact)
5. Simulation of different design combinations
6. Summary
7. Outlook

1. Introduction

Background:

- Temperature probes record the temperatures of media and in doing so exhibit a latency period
- Applications benefit from higher temporal temperature resolution (e.g. energy cost billing)



Motivation:

- Optimization of the temperature probe design for metrological properties
- Avoidance of complex series of prototypes
- Finding “better” designs when limited by standards

Aim:

- Simulation of prototypes using the “finite element method” (FEM) with validating measurements
- Evaluation of the influences of sensor position, choice of material and material thickness

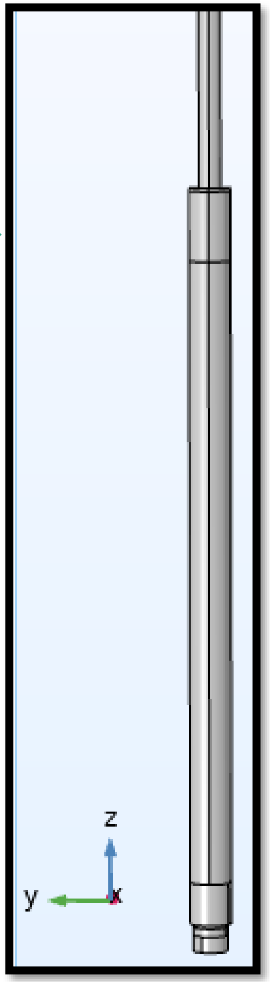
2. Setup model (geometry)

- A prototype without a final design (focus on cap of the probe)

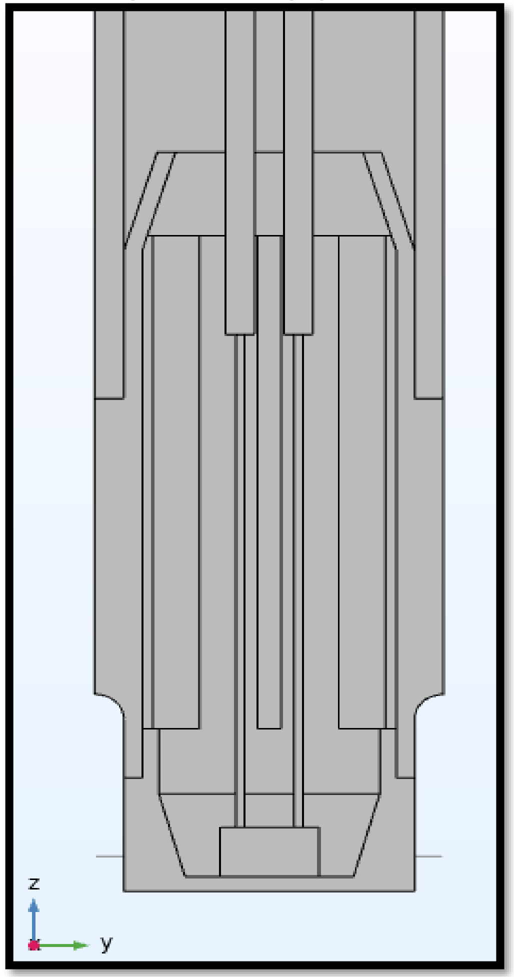
„digital twin“

- Sensor is soldered to the inside of the cap
- 2-conductor via strand cross section
- Response time determined based on the average volume temperature of the sensor
- Assumption of ideal connection between sensor and cap (no thermal resistance)

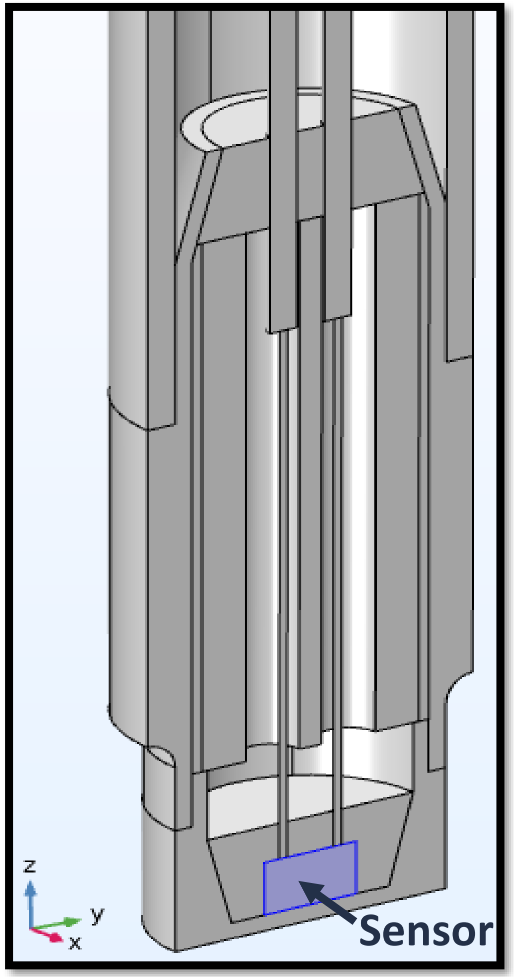
Entire probe



Front view (crosssection in symmetry plane)

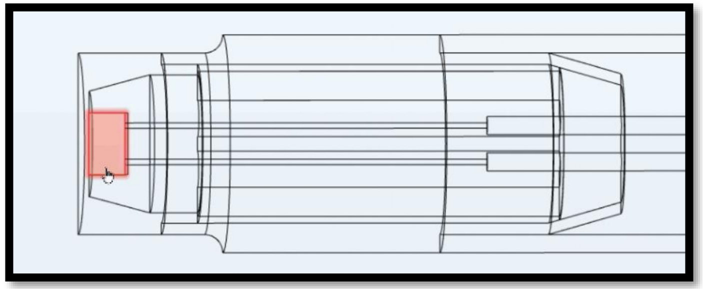


Isometric view (without air)



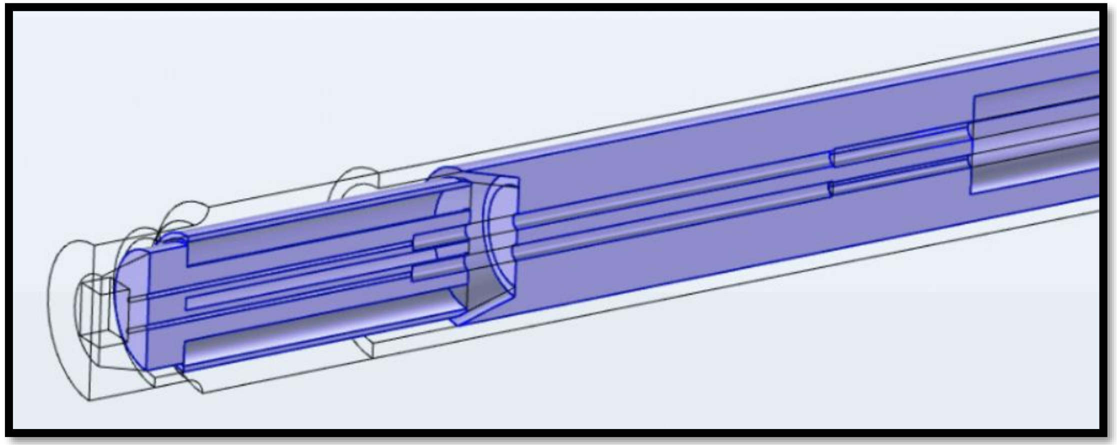
2. Setup model (physics)

- **Heat transport**
  - **Assumption of “ideal” mechanical connections**
  - **Radiation to the environment as a boundary condition**



- **Forced, turbulent flow**
  - **Inlet and outlet boundary conditions**

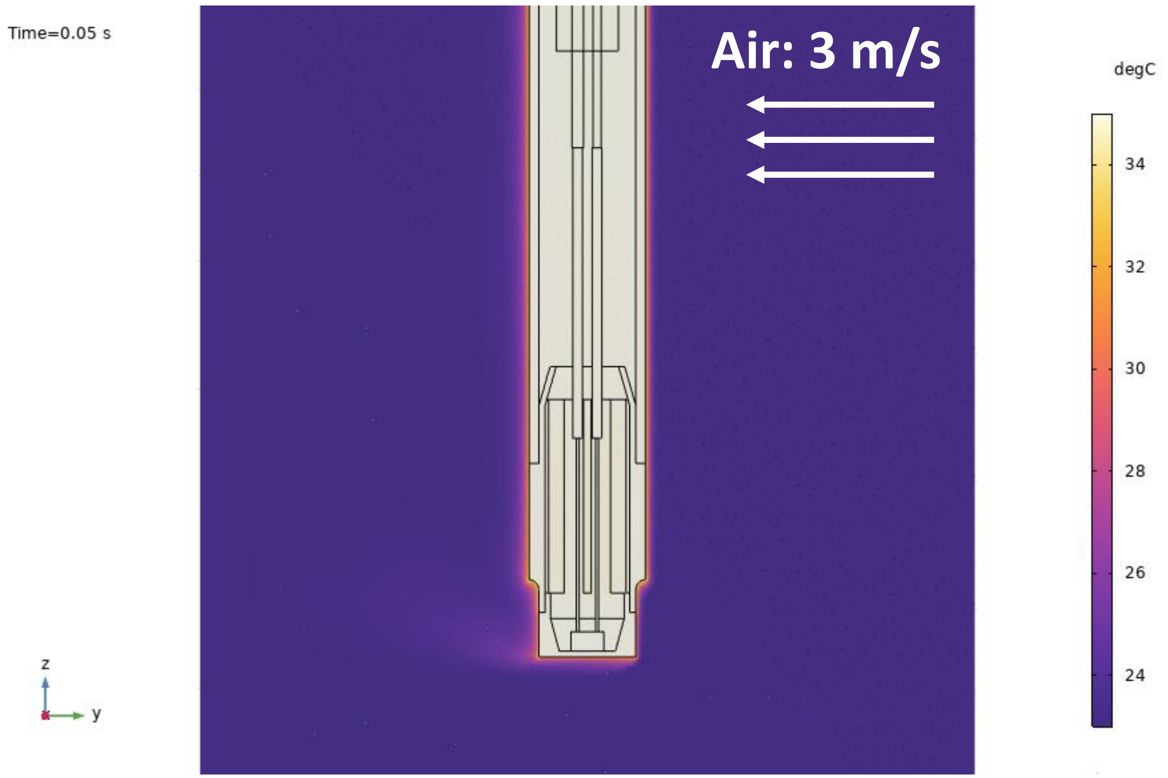
- **Natural convection (inside)**
  - **Low contribution (Rayleigh number)**
  - $Ra = \frac{\rho^2 \beta\, g\, c_p}{\mu\, k} L^3 \Delta T \rightarrow$ **Ex: Ra (L = 5 mm, ΔT = 3 K) = 100**



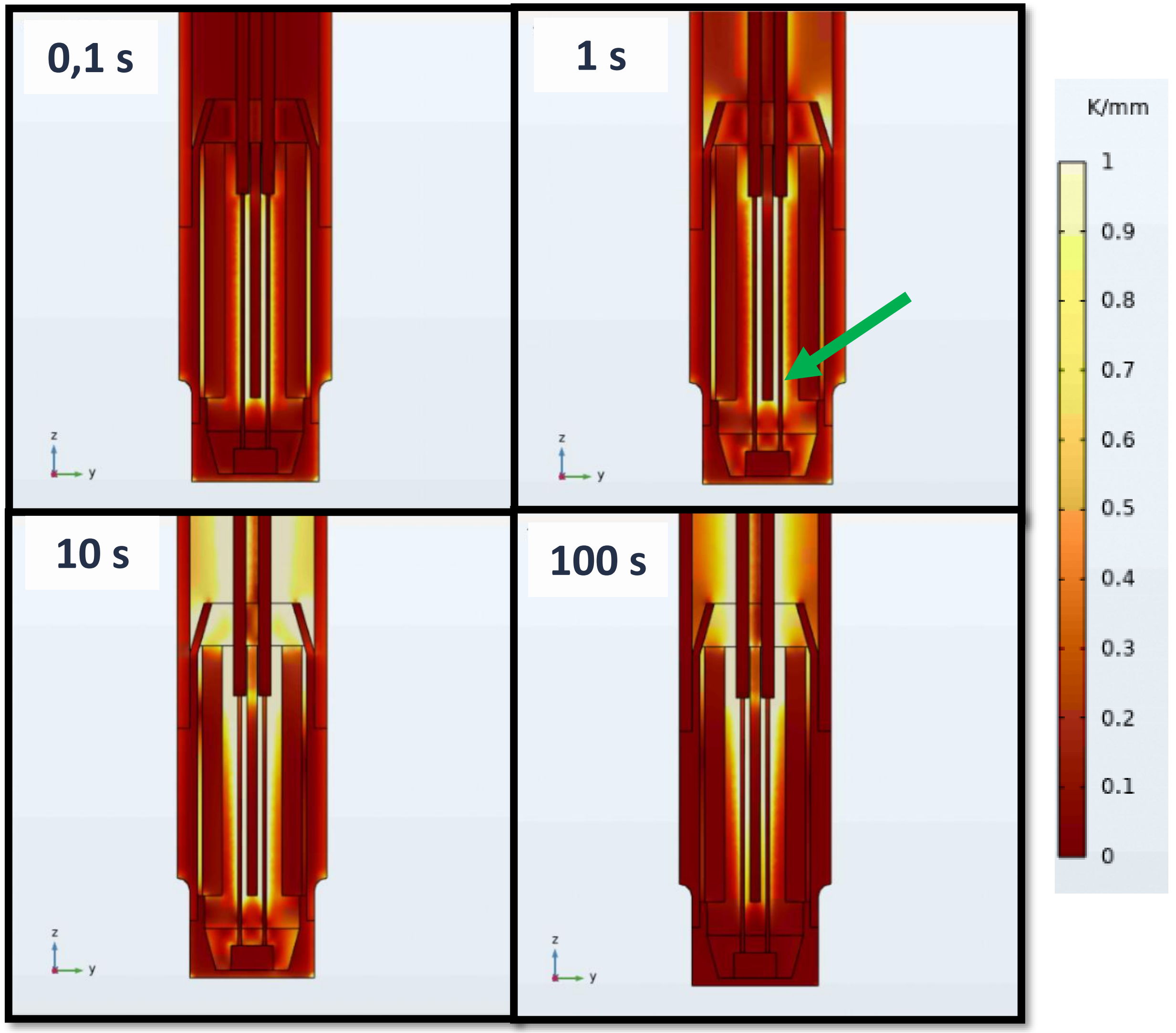
- **Thermal radiation exchange (inside)**

3. Simulation A: Validierung „Grundaufbau“

- **Transient or temporal cooling behavior according to DIN EN 60751 in air**
- **Temperature gradient pronounced around connecting wires** *

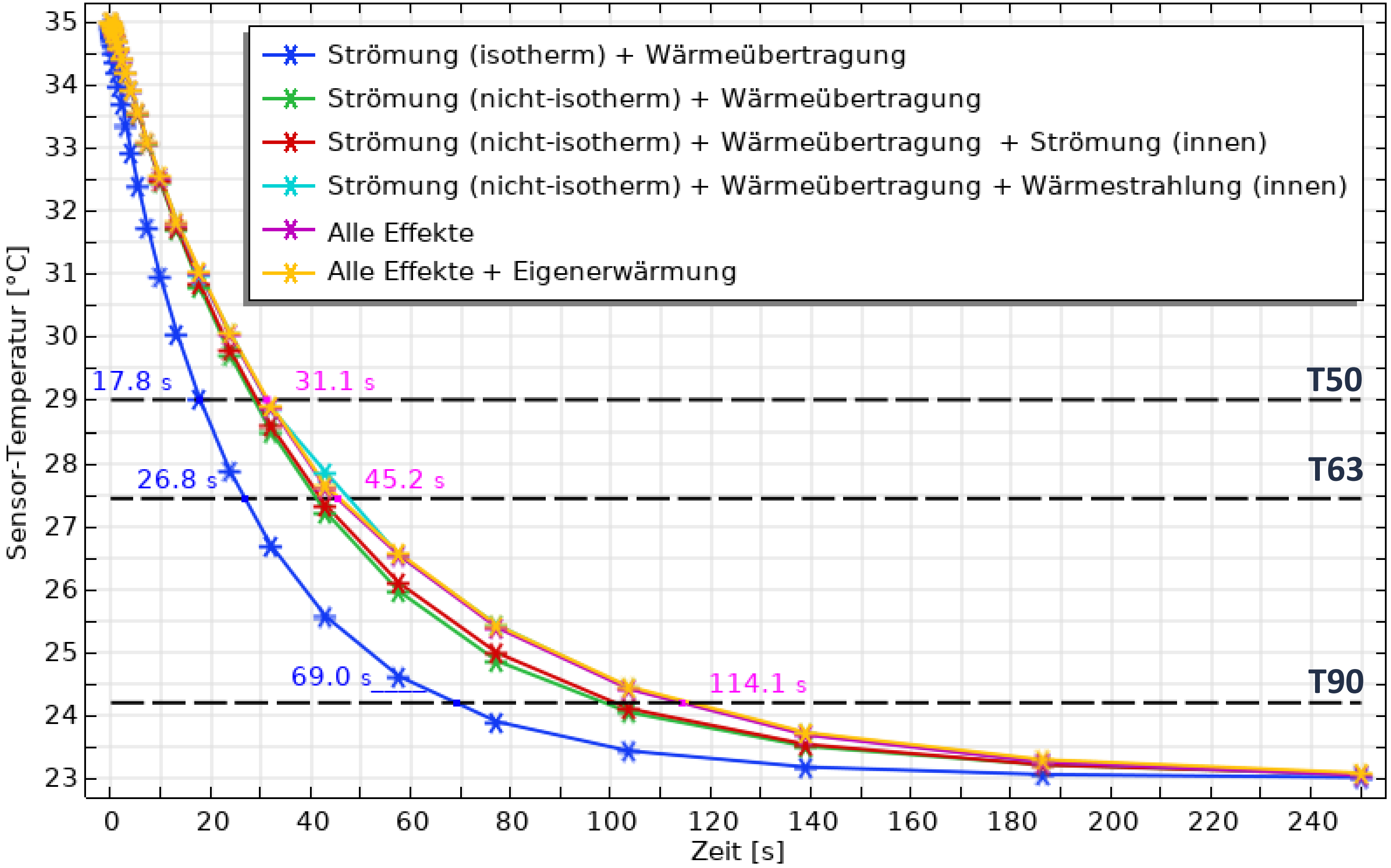


Temperature gradient



- **Non-isothermal (air) flow required**
- **Natural convection inside the sensor is negligible (green/red)**
- **After adding thermal radiation, all necessary effects are taken into account**
- **No influence from self-heating**

- **→ Depending on the effect taken into account, response times change by a factor of 1.7**



3. Simulation A: Validation „basic setup“

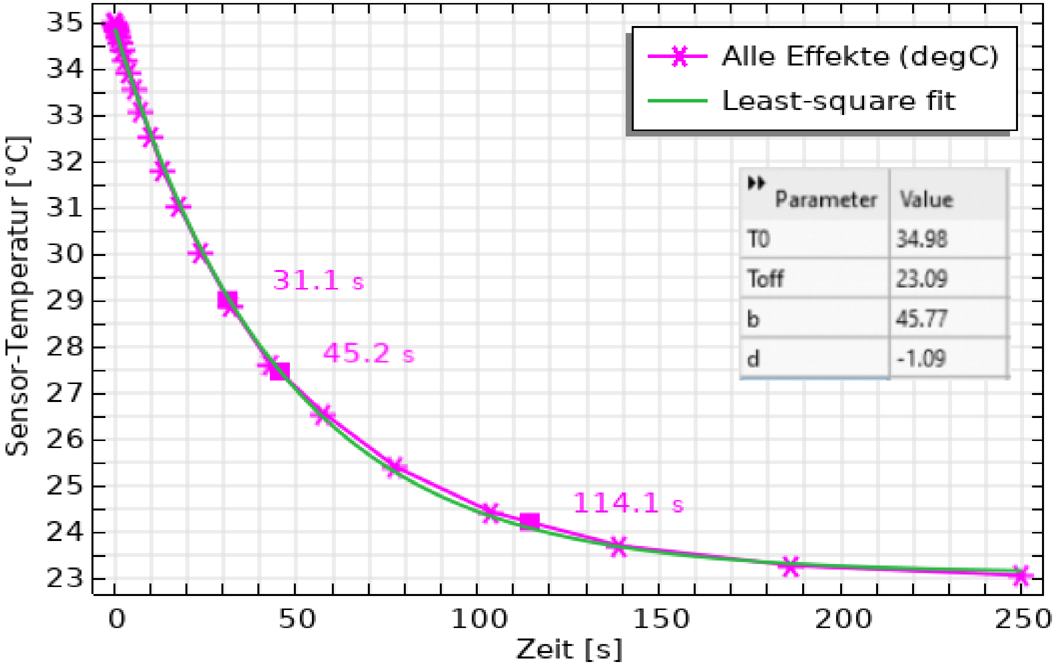
- **Comparison with measured values (n = 10)**
- **Non-linear regression for cooling process**

Temperature progression over time (cooling down)

$$T(t) = T_0 \cdot e^{-\frac{t}{b}+d} + T_{Off}$$

T_0: Initial temperature [°C]
T_{Off}: Final temperature [°C]
b: Coefficient (stretching, compression) [$\frac{1}{s}$]
d: Coefficient (shift in time axis) [1]

- **→ Simulated values agree with measurements**

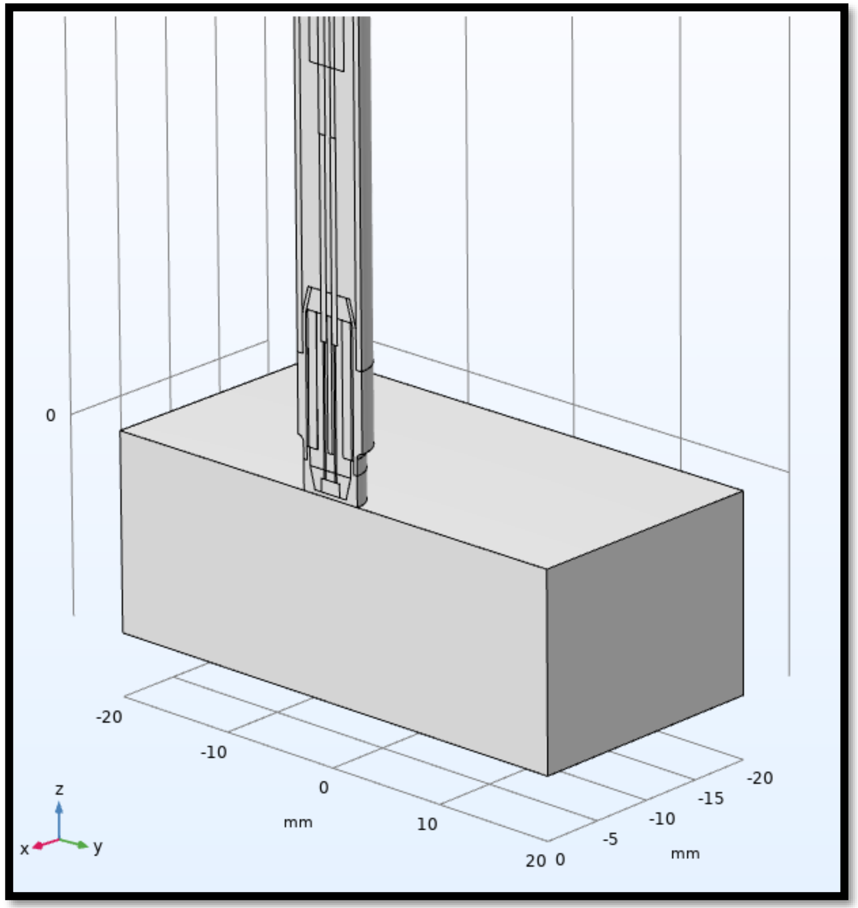


	T_{target} [°C]	$t_{simulated}$ (interpol.) [sec]	$t_{measured}$ [sec]	$t_{simulated}$ (regression) [sec]
t50	29,0	31	29,5±2,2	31,2
t63	27,4	46	42,7±2,6	45,0
t90	24,2	110	103,6±2,7	104,9

JUMO

Measuring scenario heating process:

- Contact measurement on a steel block with a defined force of 30 N
- Ambient air 23°C and steel block with two cases: T = 85°C and T = 35°C
- Thermal contact: surface roughness Rz = 6 µm, roughness slope m = 0.5 and emissivity 0.65
- Simulation without thermal paste (WLP)



- **Sensor has poor thermal coupling due to contact measurement**

- **Poor coupling visible at t90**

  → Thermal step response influenced by limited heat flow (contact) and mass of the sensor

  → Behavior visible in both cases

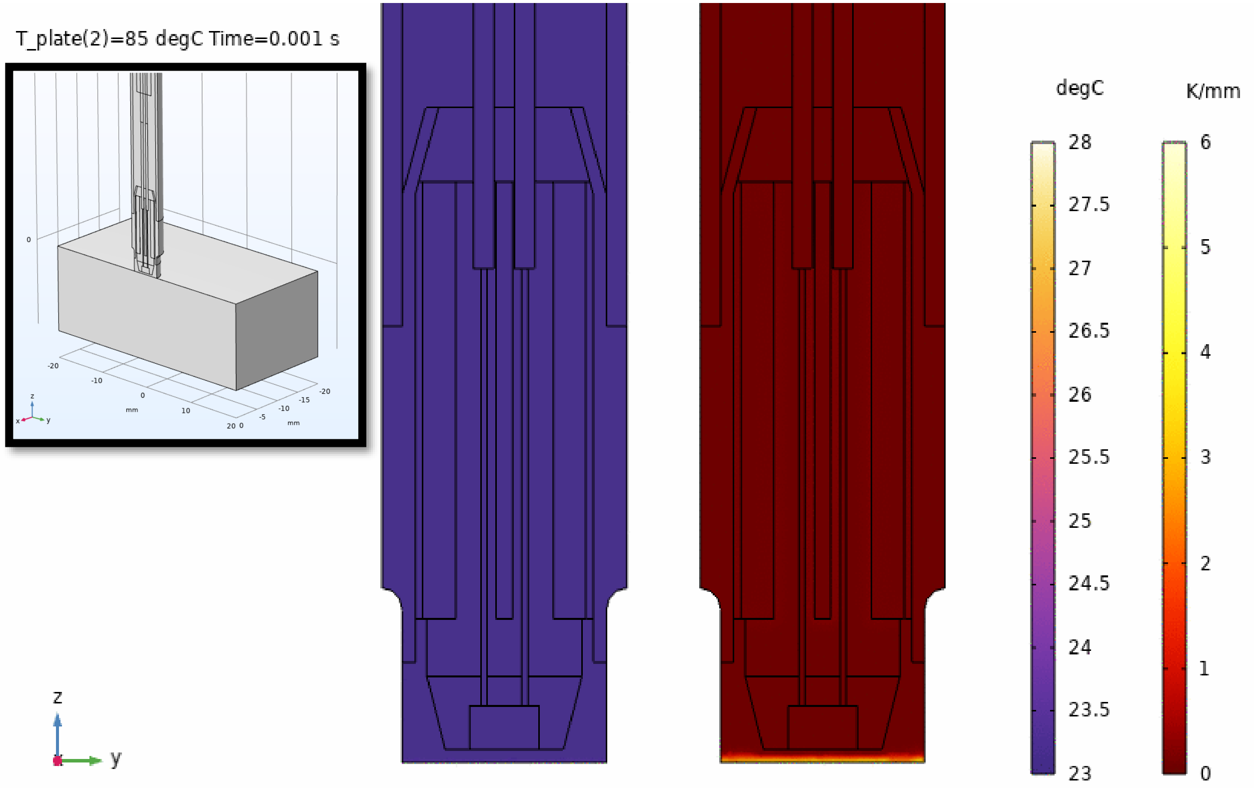
T = 85 °C

	T_{target} $[°C]$	$t_{simulated}$ $[sec]$
t50	48,4	2,0
t63	55,0	3,7
t90	68,7	31,5

T = 35 °C

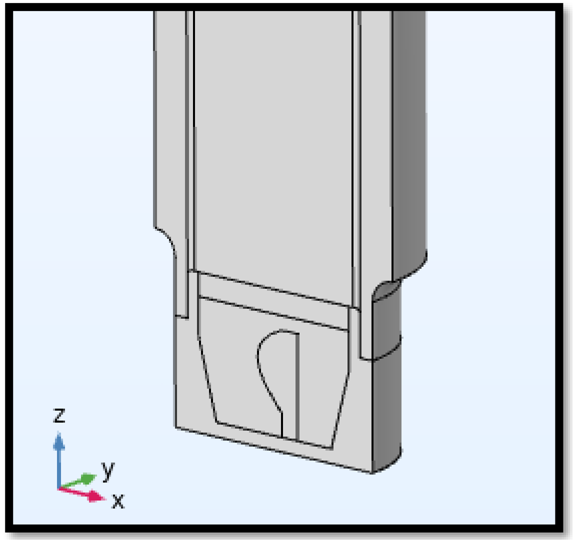
	T_{target} $[°C]$	$t_{simulated}$ $[sec]$
t50	28,0	2,2
t63	29,3	4,3
t90	32,0	38,0

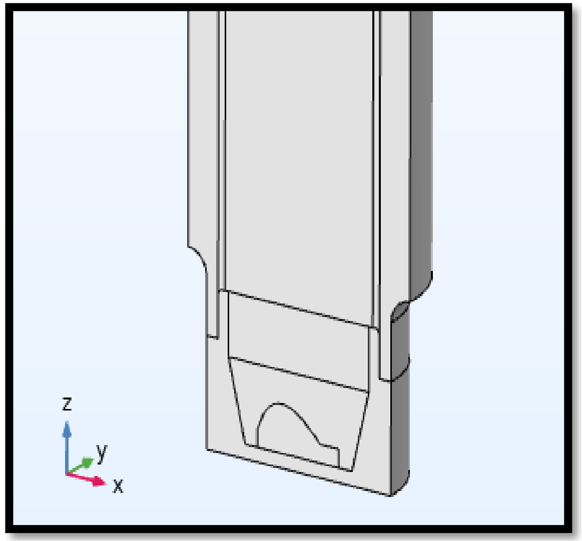
Heating process for T = 85 °C



5. Simulation of different design combinations

- <u>Variation 1:</u> Sensor position flat / standing
- <u>Variation 2:</u> With thermal paste / without thermal paste
- <u>Variation 3:</u> Bottom thickness [0.3 mm to 0.9 mm]
- Response time according to DIN EN 60751 in water





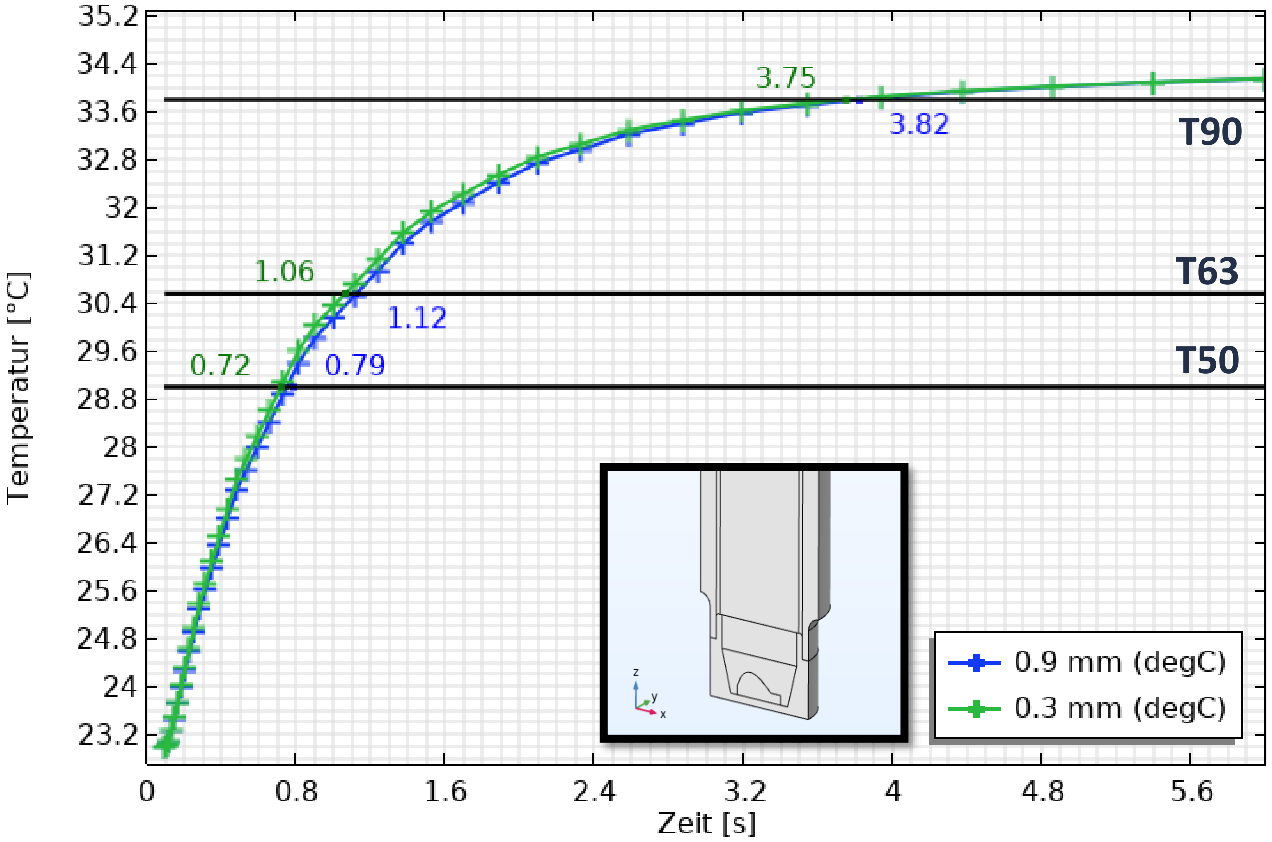
<u>Question:</u>

- What is the relative response between the design variations?
- → No extra validation through measurements in the concept phase here

5. Simulation C: „horizontal orientation of sensor“

- **Varying the soil thickness by a factor of 3 changes the response time by approx. 10%**
- **Shortest response times without thermal paste**
  - **Difference at t90**
  - **A design does not necessarily have to be the best in all three metrics**

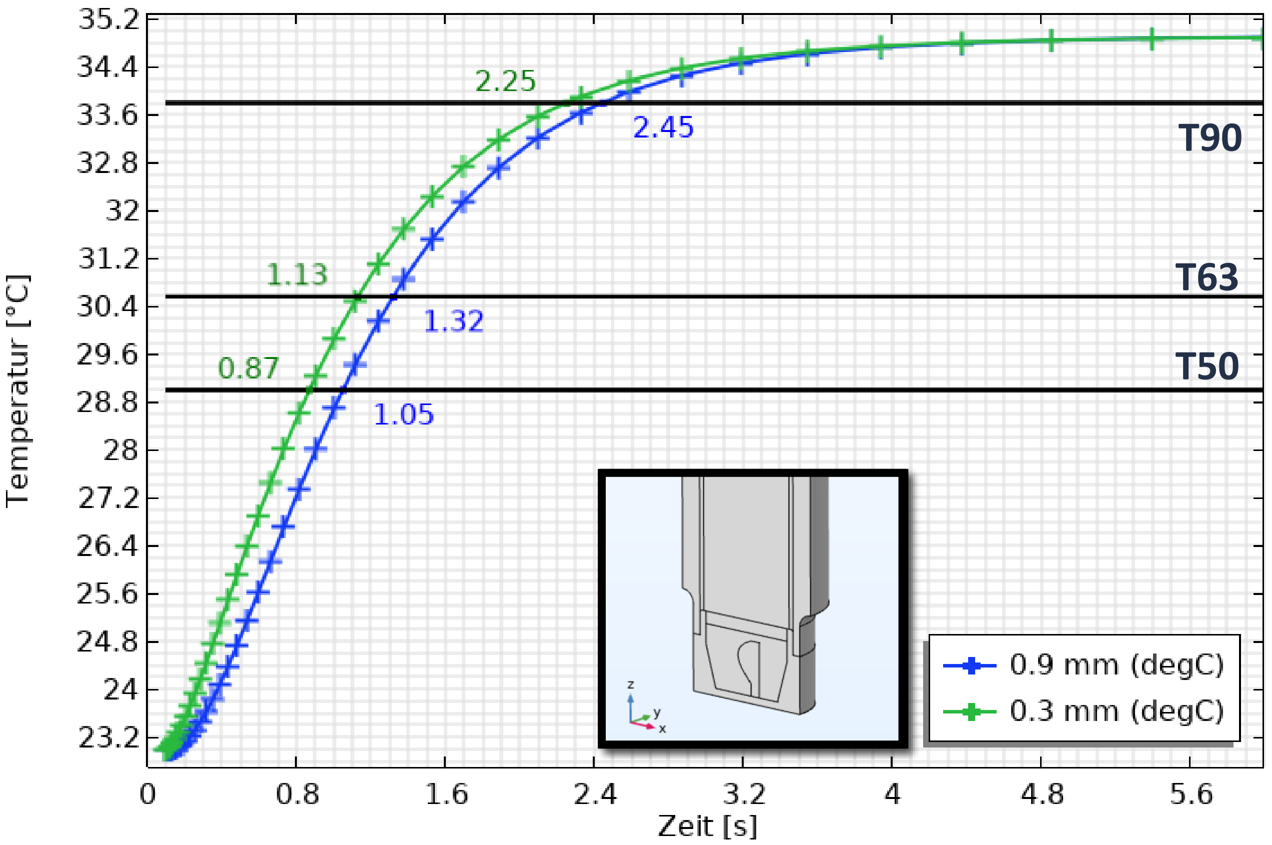
Bottom thickness [mm]	response time t50 [s]	response time t63 [s]	response timet90 [s]	thermal paste
0,3	0,76	1,09	3,56	yes
0,5	0,78	1,11	3,63	yes
0,7	0,79	1,14	3,66	yes
0,9	0,79	1,13	3,69	yes
0,3	0,72	1,06	3,75	no
0,9	0,75	1,12	3,82	no



5. Simulation D: „standing orientation of sensor“

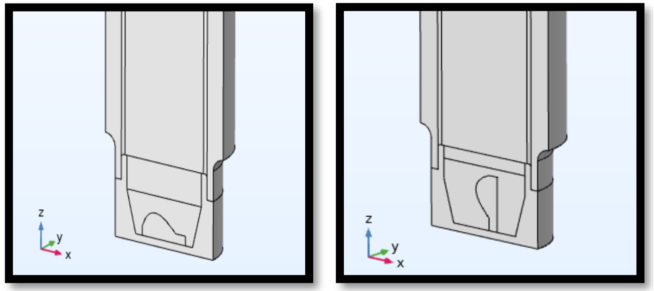
- **t50 and t63 are a factor of 2 larger than with the “lying sensor” variation**
- **Shortest response time without thermal paste**
  - **Design is best for all three metrics**

Bottom thickness [mm]	response time t50 [s]	response time t63 [s]	response timet90 [s]	thermal paste
0,3	1,50	2,03	4,08	yes
0,5	1,56	2,08	4,12	yes
0,7	1,63	2,16	4,20	yes
0,9	1,65	2,16	4,20	yes
0,3	0,87	1,13	2,25	no
0,9	1,05	1,32	2,45	no



5. Simulation: Comparison of different designs

- Variation “horizontal orientation” fastest at t50 and t63
- Variation “standing orientation” faster at t90
    - More connection wire in the sensor tip



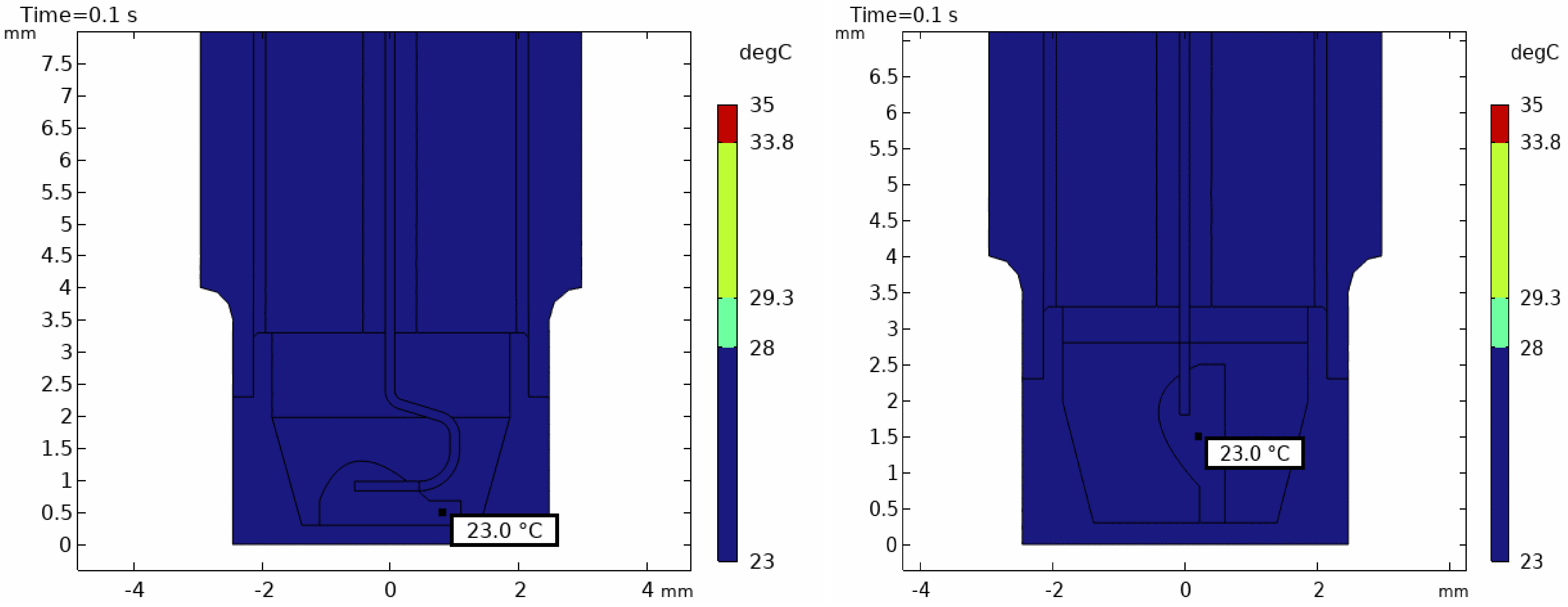
horizontal orientation

Bottom thickness [mm]	response time t50 [s]	response time t63 [s]	response timet90 [s]	thermal paste
0,3	0,76	1,09	3,56	yes
0,5	0,78	1,11	3,63	yes
0,7	0,79	1,14	3,66	yes
0,9	0,79	1,13	3,69	yes
0,3	0,72	1,06	3,75	no
0,9	0,75	1,12	3,82	no

standing orientation

Bottom thickness [mm]	response time t50 [s]	response time t63 [s]	response timet90 [s]	thermal paste
0,3	1,50	2,03	4,08	yes
0,5	1,56	2,08	4,12	yes
0,7	1,63	2,16	4,20	yes
0,9	1,65	2,16	4,20	yes
0,3	0,87	1,13	2,25	no
0,9	1,05	1,32	2,45	no

5. Simulation: Comparison of different designs



6. Summary

- <u>Question</u>: Which design changes lead to an improvement in the response time?

- Successful validation of the transient simulation with measured values
- Evaluation of different measurement scenarios during the design phase
- Evaluation of possible designs before sample construction (10 sample types or 100 test specimens)

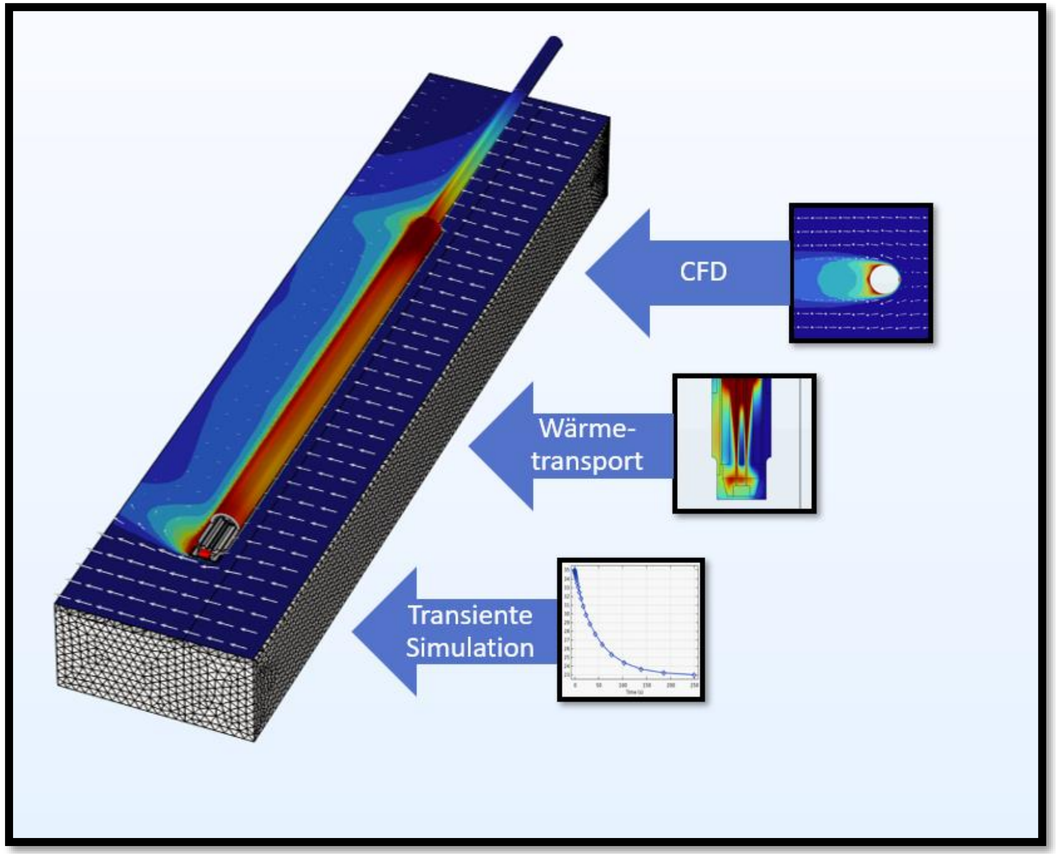
- → Understanding of physical phenomena for future developments

- → Concrete design recommendation for optimal performance

- → Successful description of measurement scenarios using FEM simulation

7. Outlook

- **Replication of measurement scenarios**
  - **Heat dissipation error according to standard**
- **Environmental conditions that cannot be tested (e.g. high temperature)**
- **Pipe flows with different installation situations**
- **Determination of parameters (temperature, flow) on geometries that are difficult to access (e.g. in heat meters)**



Contact

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Attachment 1: Response behavior in water

	T_{Soll} $[°C]$	$t_{simuliert}$ (interpol.) [sec]	$t_{gemessen}$ $[sec]$
t50	29,0	0,6	0,40±0,24
t63	30,6	0,8	0,6±0,4
t90	33,8	1,7	1,43±0,23