Quick determination of the manufacturing performance of a direct- fired industrial furnace using an implicitly solved, multiple 1D approach

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Aachen, 08.10.2021

Agenda

- Objective & General Idea
- Geometrical & Mathematical Discretization
- Boundary Conditions & Results
- Outlook

Objective & General idea

Objective:

Reduce the computational time and the required computational power to estimate the average temperature distribution within an industrial furnace

Expected Benefits:

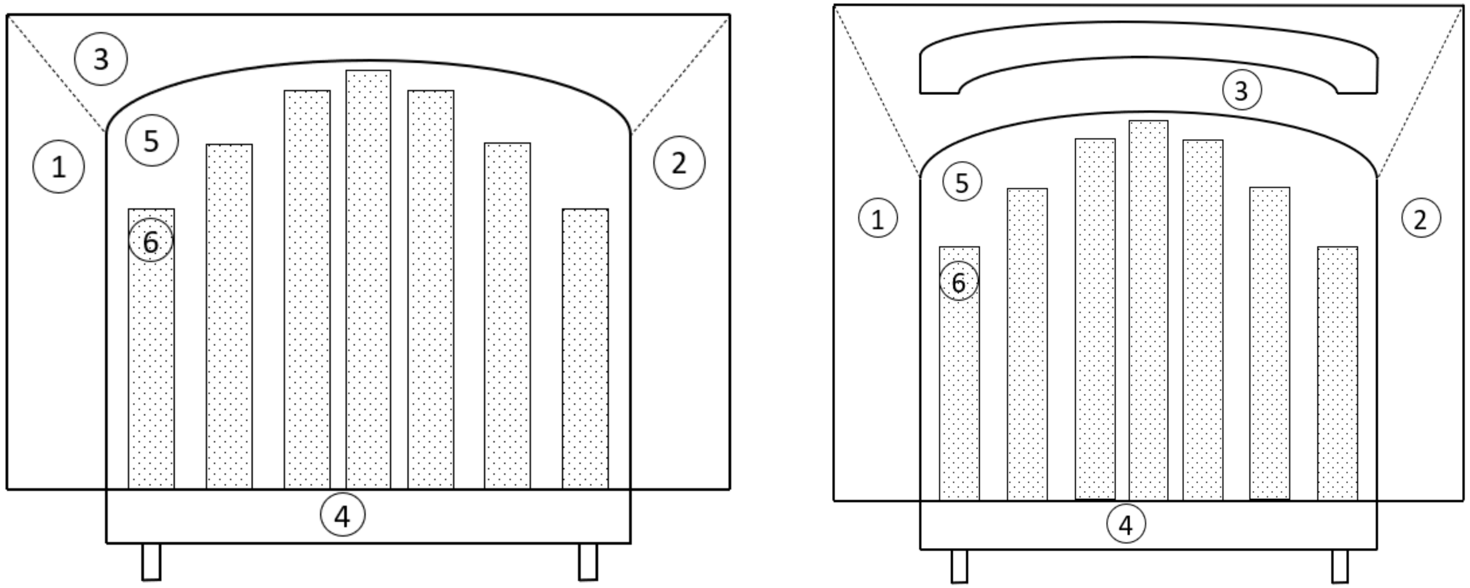
- Better understanding of heat transfer within furnace without measurement equipment
  → Digital sensor
- Better knowledge of fuel/ power consumption when changing operating conditions for new products
  → Initial parametrization
- Estimation of product properties using temperature- property relationships

→ **How to implement this?**

Objective and General Idea

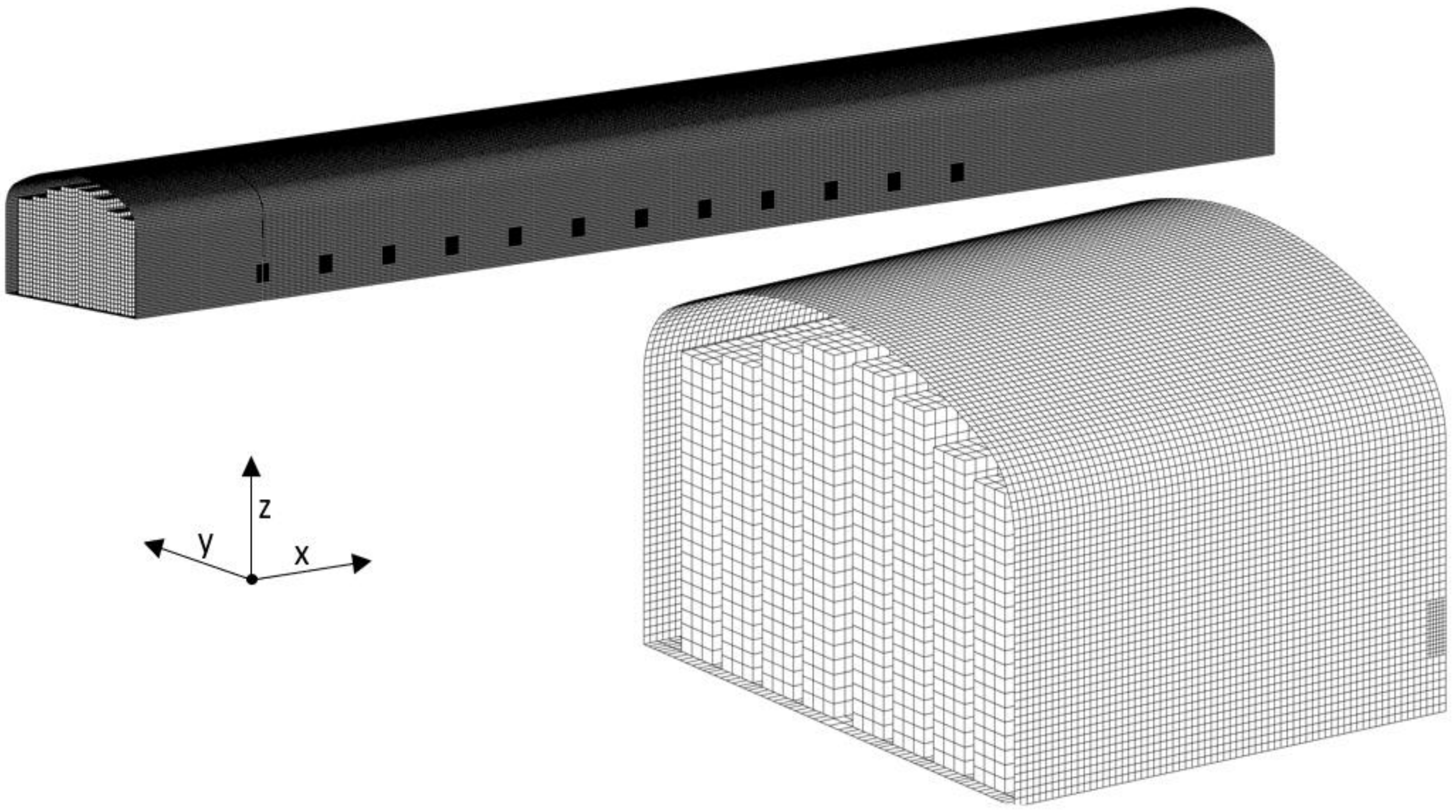
Idea: Simplified subdivision of geometrical domain into separate one- dimensional zones

Example: Tunnelfurnace producing stacked refractory bricks



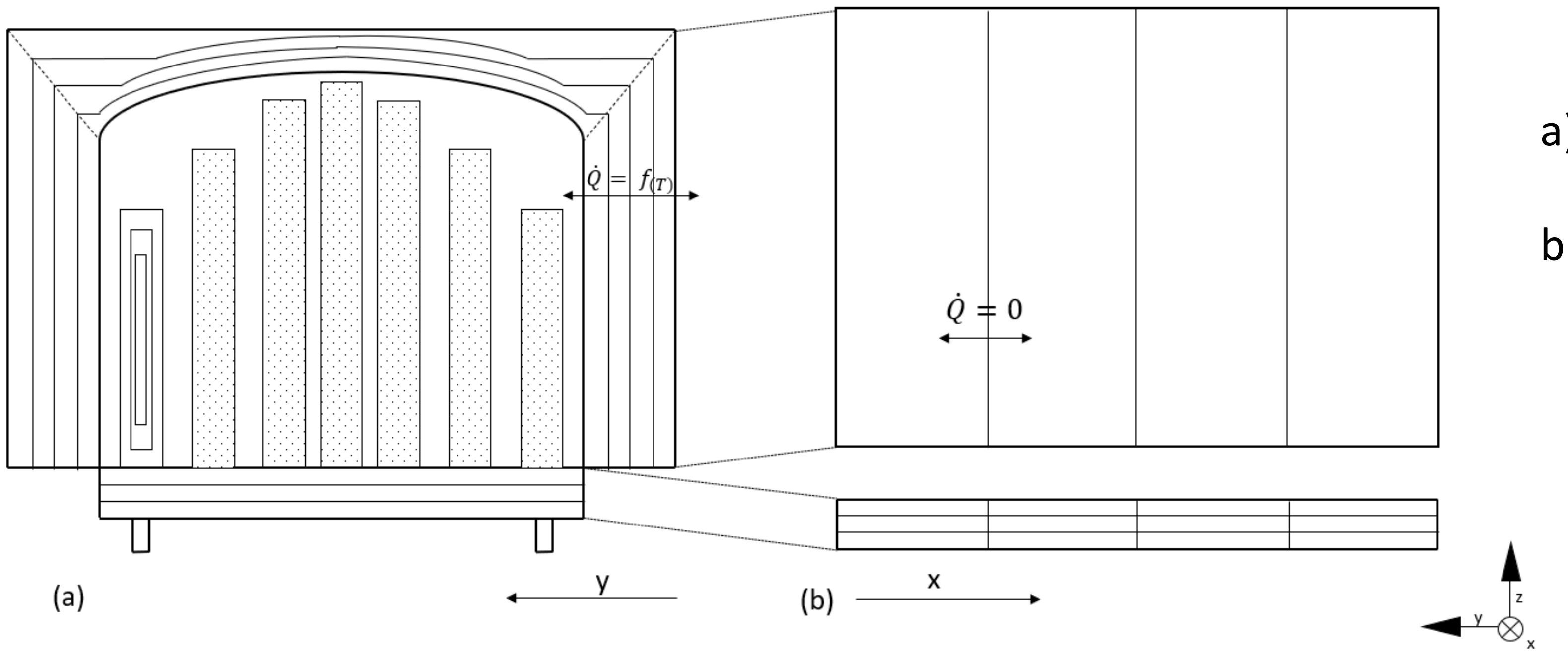
1 & 2: side wall segments
3: ceiling segments
4: kiln cart platform
5: atmosphere segments
6: product stacks

Geometrical & Mathematical Discretization



Observed simulation geometry of furnace inside surfaces and product outside surfaces

Geometrical & Mathematical Discretization



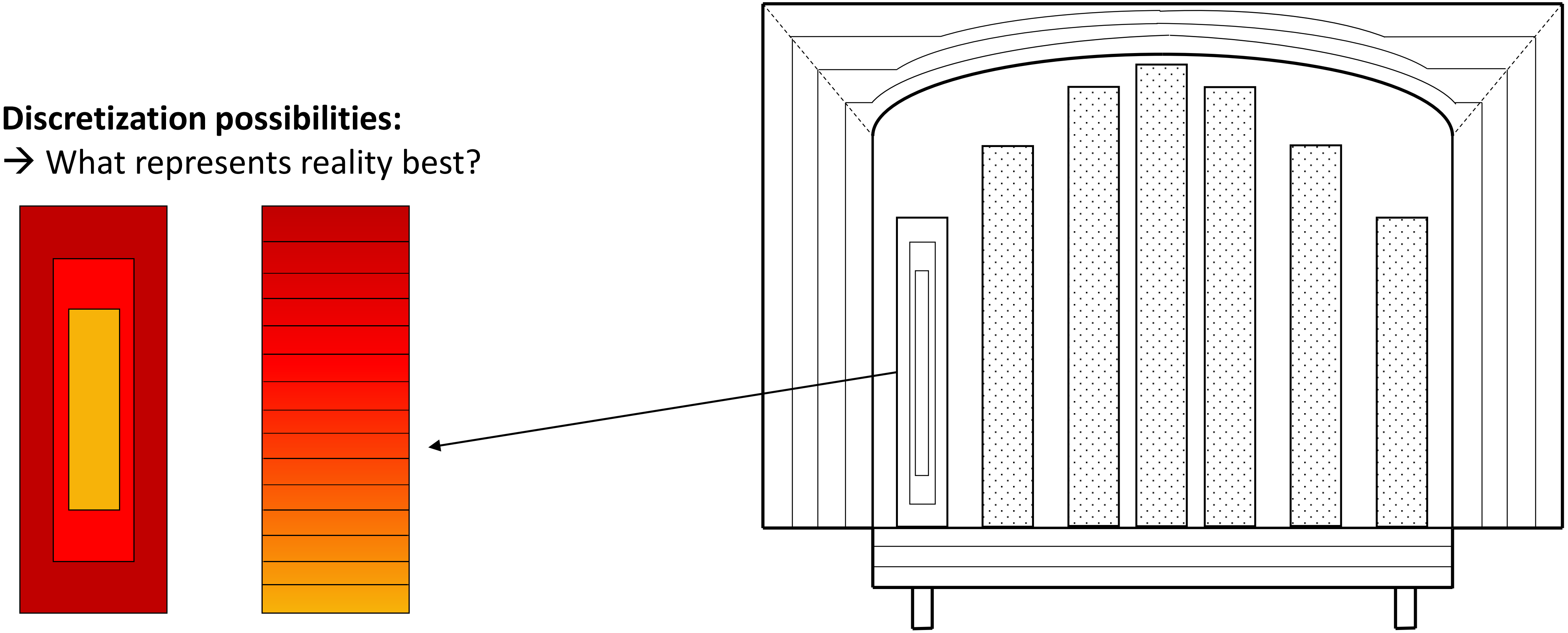
a) Furnace cross- section discretization layers
b) Side wall and kiln cart platform discretization layers

<u>Heat can only be transferred along the respective one- dimensional zone and exchanged between different zones</u>

Geometrical & Mathematical Discretization

Discretization possibilities:

→ What represents reality best?



(a) (b)

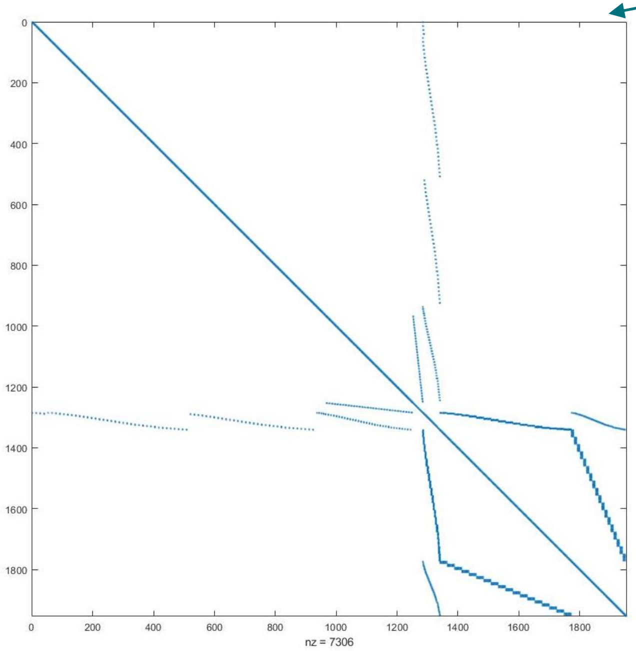
a) Concentric discretization →
b) Linear discretization

Concentric representation in this case better because of low thermal conductivity of product material and stack measurements

Geometrical & Mathematical Discretization

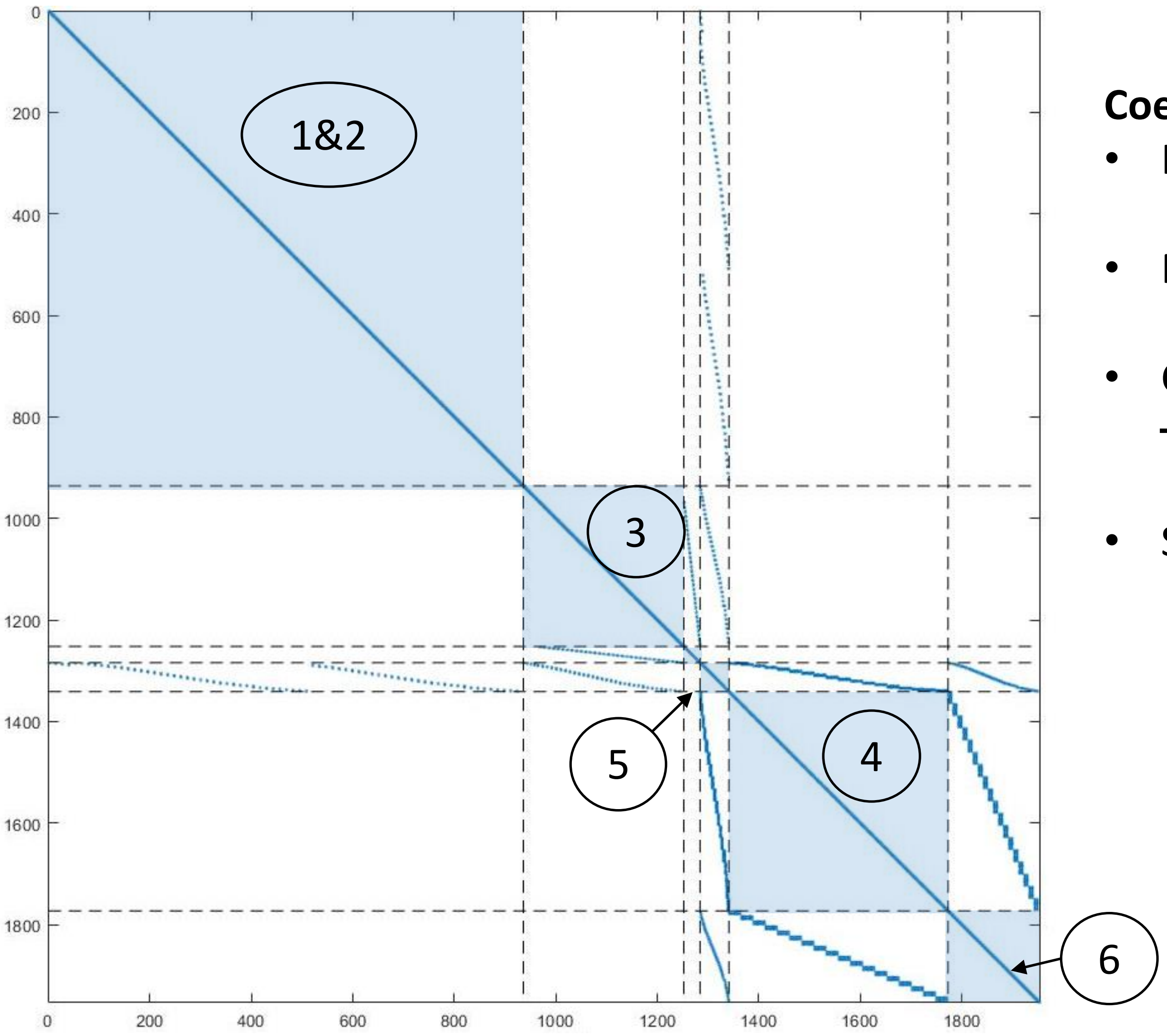
$$ld\, T_{i-1}^{n+1} + md\, T_i^{n+1} + ud\, T_{i+1}^{n+1} + rad\, T_j^{n+1} + rad_2 T_k^{n+1} = \text{RHS}$$

$$A\,T = RHS$$



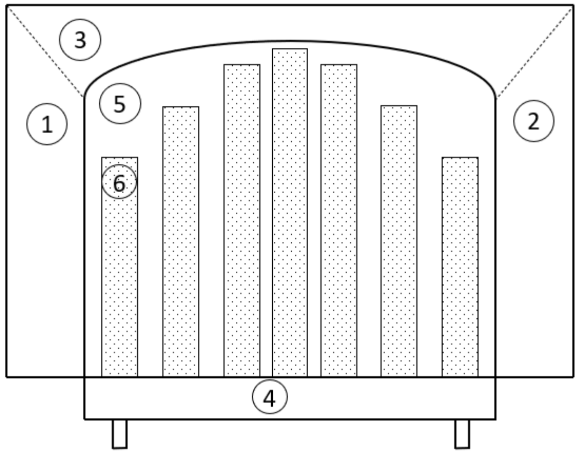
$$\begin{bmatrix} T_{RB1} \\ T_{RB2} \\ T_{RB3} \\ T_1 \\ T_2 \\ . \\ . \\ . \\ T_{1919} \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \\ sourceterm_1 + accumulationterm_1 + radiationterms_1 \\ sourceterm_2 + accumulationterm_2 + radiationterms_2 \\ . \\ . \\ . \\ sourceterms_{1919} + accumulationterms_{1919} + radiationterms_{1919} \end{bmatrix}$$

Geometrical & Mathematical Discretization



Coefficient Matrix:

- Indicates connectivity between each cell
  → Describes which cell can transfer heat to another cell
- Radiation terms are placed explicitly on RHS, thus
  no communication between zones 1&2 and zones 6 are visible
- Coefficient matrix is dynamic
  → Different Stack patterns possible, resulting in a variation of cell amount
- Source terms are placed explicitly on RHS



Geometrical & Mathematical Discretization

Surface to Surface model:

- Radiation is a surface phenomenon and depends on how the surfaces are exposed to each other
  → Participating media are neglected

1) Energy Flux leaving a surface can be expressed as:

$$q_{out_i} = \varepsilon_i \sigma T_i^4 + \rho_i \sum_{j=1}^{N} F_{ji} q_{out_j} \quad \equiv \quad J_i = E_i + (1 - \varepsilon_i) \sum_{j=1}^{N} F_{ji} J_j$$

2) This can be expressed in matrix form:

$$KJ = E$$

$$K = \begin{bmatrix} 1 & (\varepsilon_1 - 1)F_{12} & (\varepsilon_1 - 1)F_{13} & (\varepsilon_1 - 1)F_{14} & (\varepsilon_1 - 1)F_{15} & \dots \\ (\varepsilon_2 - 1)F_{21} & 1 & (\varepsilon_2 - 1)F_{23} & (\varepsilon_2 - 1)F_{24} & (\varepsilon_2 - 1)F_{25} & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix} \quad J = \begin{bmatrix} q_1 \\ q_2 \\ \vdots \end{bmatrix} \quad E = \begin{bmatrix} \varepsilon_1 \sigma T_1^4 \\ \varepsilon_2 \sigma T_2^4 \\ \vdots \end{bmatrix}$$

J corresponds to the flux leaving the surface → net flux of surface can be computed

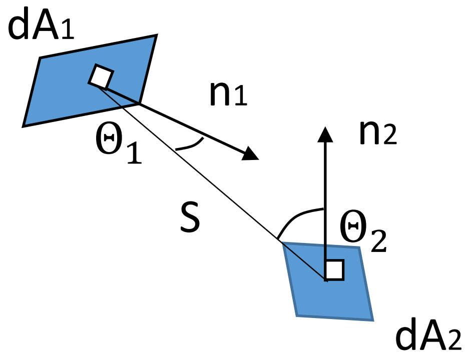
Geometrical & Mathematical Discretization

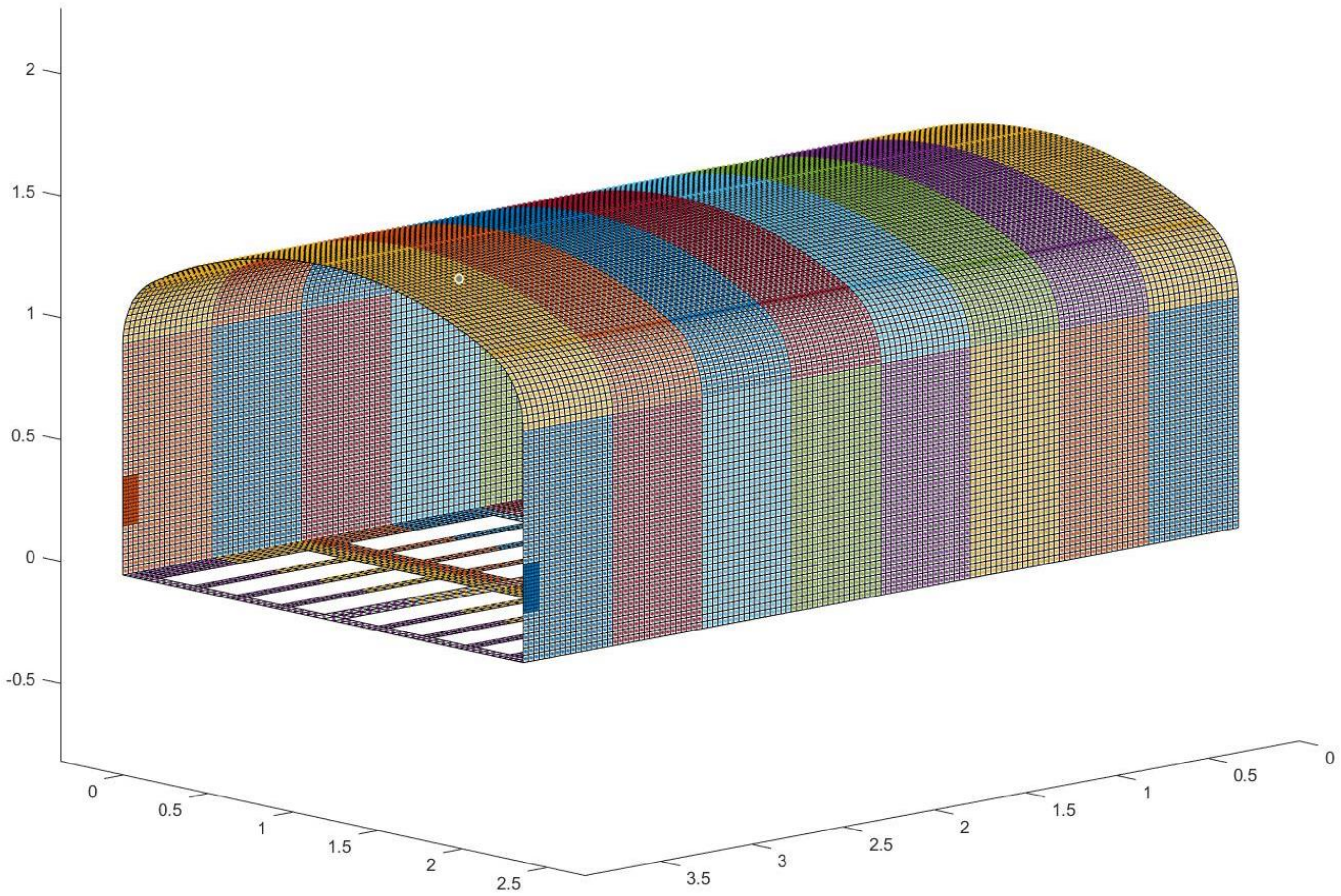
Computation of view factor

<u>Macroscopic surfaces:</u>
→ Corresponds to simulation cell size

<u>Microscopic surfaces:</u>
→ Required to pre- compute view factors via numerical integration

$$dF_{ij} = \frac{1}{A_i} \int_{dA_1} \int_{dA_2} \frac{\cos \Theta_1 \cos \Theta_2}{\pi S^2} \delta_{12} dA_1 dA_2$$

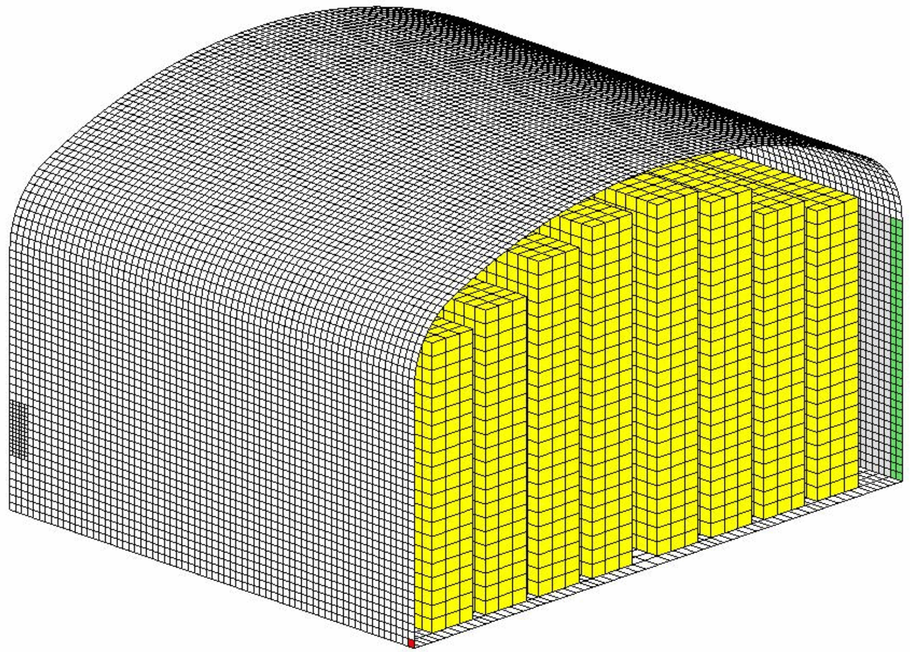


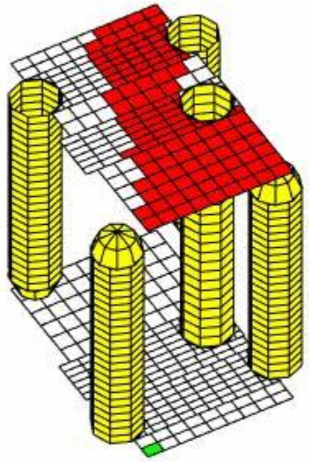


Geometrical & Mathematical Discretization

Computation of view factor

- Changing geometry if stack pattern of product changes
  → Re- computation of view factor matrix required
- One matrix for each geometry required
  → Highly time- consuming if performed on complete furnace
  → Separation into representative regions and perform sub- computations
  → While simulation runs, assembling of these regions into the current valid matrix





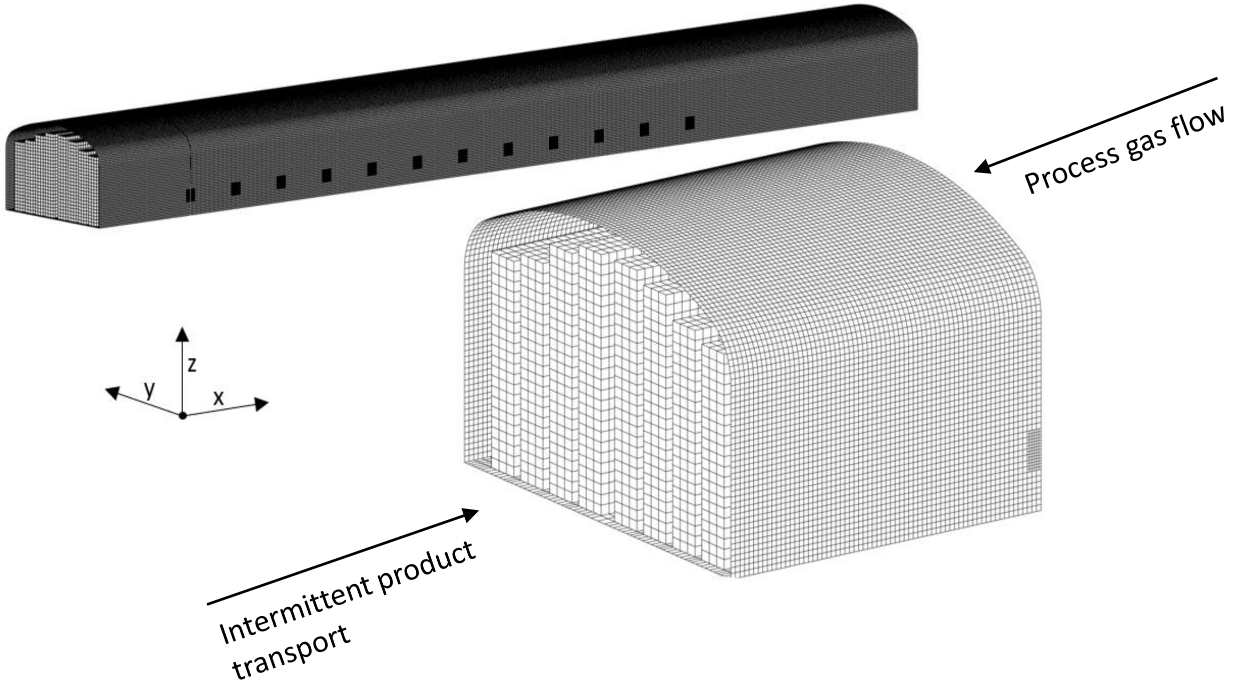
Boundary Conditions & Results

Geometry Specifications:

- Length of furnace: 15.687 m
- Width of furnace: 2.35 m → Only burning zone simulated
- Height of furnace: ~ 1.5 m

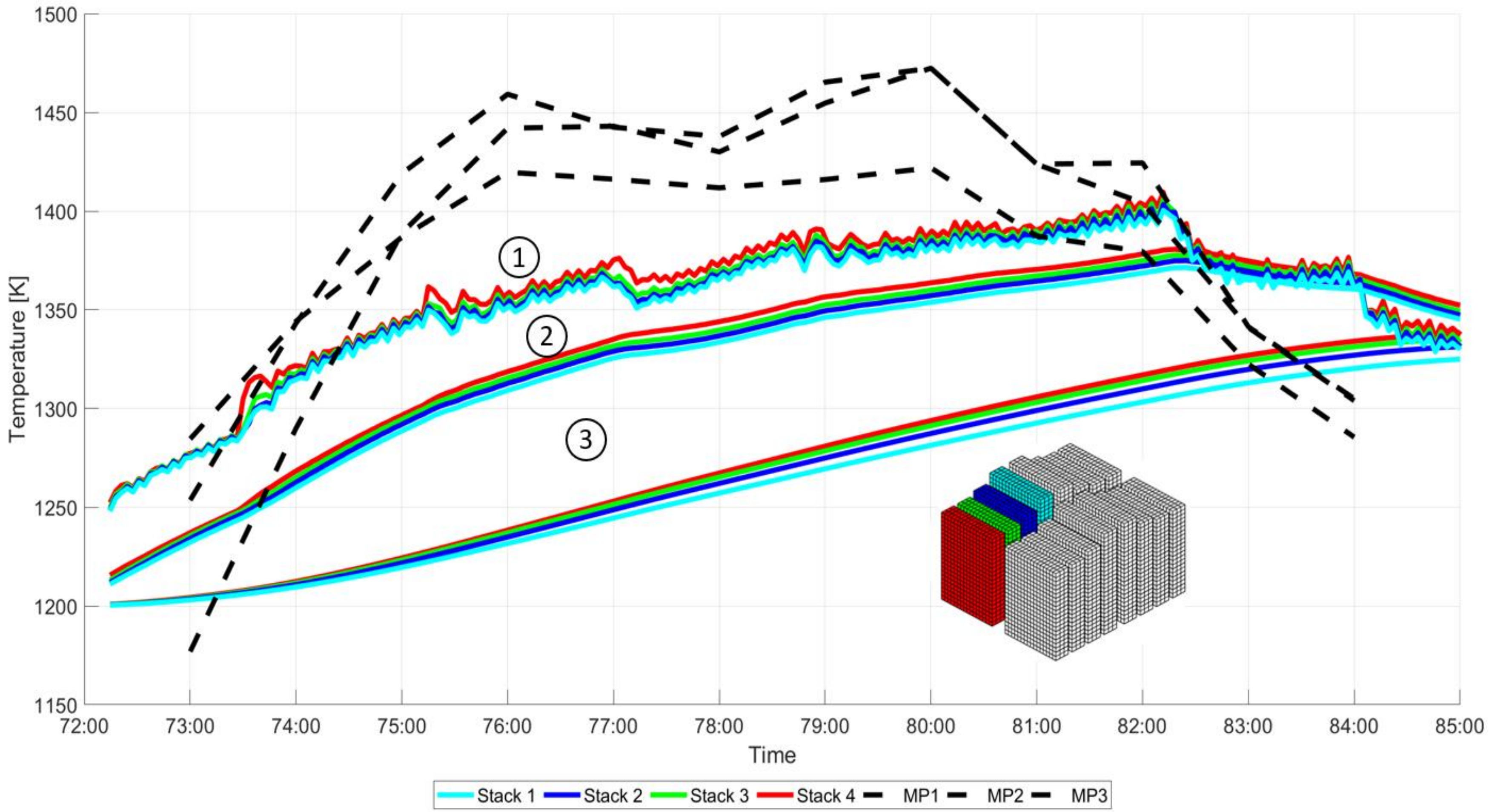
Initial Conditions:

- Counter- current process gas stream
- T_{init} of counter- current stream: 1300 K
- $\dot{m}$ of counter current stream: 0.1 kg/s
- Number of burner Pairs: 12
- Average power per burner: 85 kW – 205 kW
- Air number of burner: ~ 0.7 – 0.8
- Initial temperature of product stacks, kiln cart: ~1200 K
- Product dwell time: 105 min



Boundary Conditions & Results

Temperature profile of tracked kiln cart



--- measurement data at various product stack surface locations

Simulation

1 Average surface temperature

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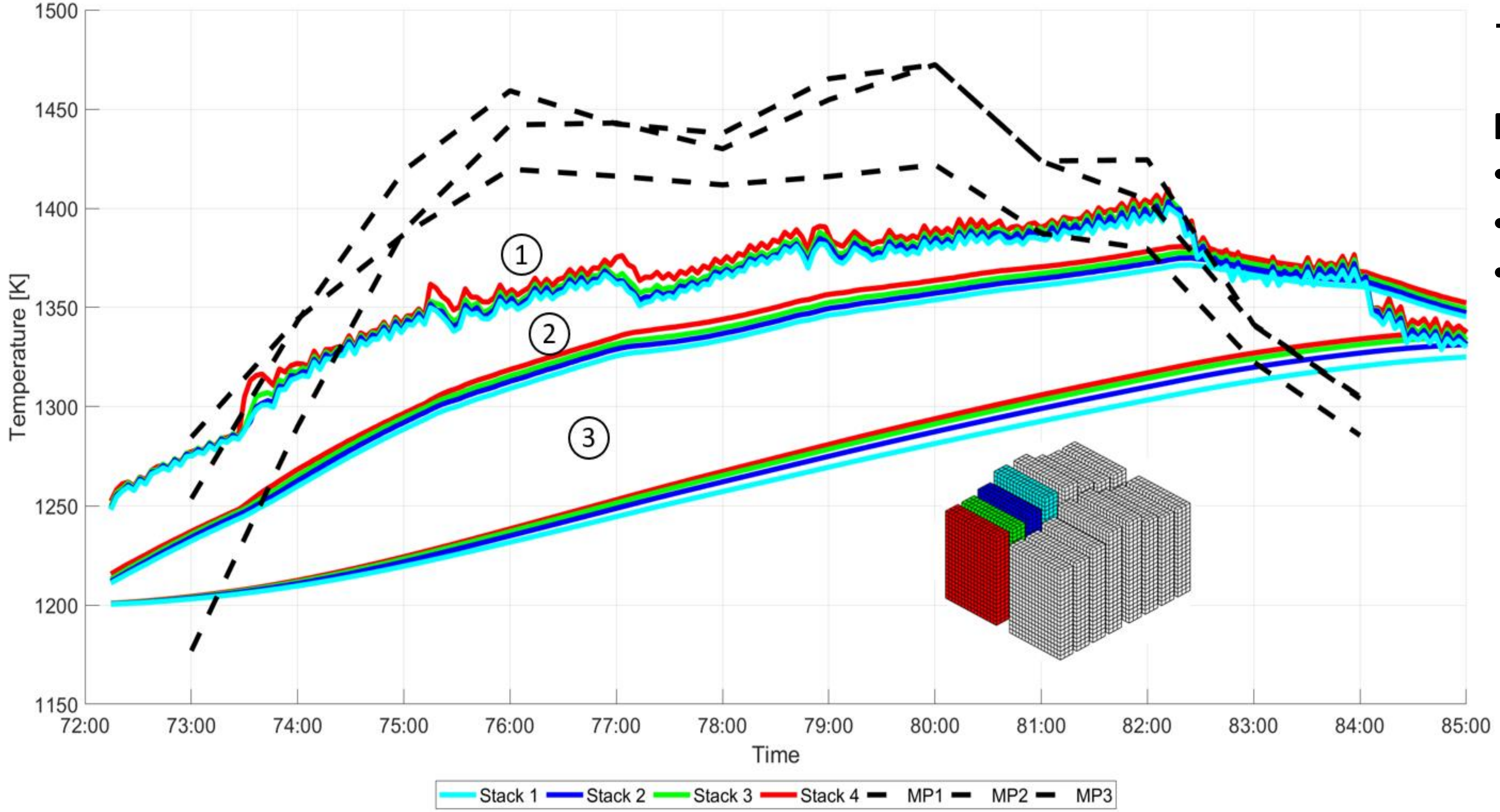
3 Average core temperature

Simulated production time of 85 hours within of 340 seconds of computational time

Boundary Conditions & Results

Direct comparison only between dashed lines and 1 possible!



→ Difference in temperature gradients

Possible Causes:

- Radiation Model (S2S)
- Secondary Reactions (excess air)
- Underestimation of heat transfer coefficient

Outlook

- Analysis of heat transfer coefficient and dwell time
  → Conduction of several simulations to evaluate impact on temperature profile

- Detailed measurement campaigns
  → Increase confidence in data
  → Yield data for analysis of secondary reactions

- Inclusion of secondary reactions
  → Excess air due to not airtight furnace
  → Sub- stoichiometric combustion provides fuel
  → Reaction between excess air and remaining fuel cause secondary source terms, which increases temperature gradient on the product inlet side

Thank you for your attention