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Modelling of an indirect-fired heat treatment line using an implicit multiple one-dimensional approach

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Abstract

The need of making quick decisions is an essential factor in today's industrial production business to stay competitive. Being up to date regarding vital decision criteria such as production and process data is difficult, raising the demand of highly developed quick decision tools. Thus, it is important to decide on the right tools capable of predicting basic process behavior without much effort. This paper presents an approach that decreases the model complexity of an indirect-fired heat treatment line for steel strips, making it possible to simulate global process parameters as for example temperature profiles at the respective furnace regions.

General

The need for data to make substantiated and important decisions is growing in order to increase the quality of products. Two accurate and state of the art methods to generate the essential data are the conduction of experiments and their accompanying monitoring of results or the remodeling of the production process and subsequent simulation using Computational Fluid Dynamics (CFD). If correctly handled, experiments can deliver accurate and reliable results but have the disadvantage of being expensive and impractical for certain industry processes. On the other hand, CFD- simulations can be carried out for almost every problem but require a lot of expertise regarding the grid generation and equation implementation for the respective simulation case. Both, experiments and CFD- simulations, are time consuming operations, which makes them impractical as a quick decision tool.

An alternative to CFD- simulations is the use of a kind of reduced furnace model shown in this paper. They only require a few input parameters that describe the general furnace geometry as well as some boundary conditions like operating parameters which are utilized to automatically set up the simulation case. The general principle of creating a reduced furnace model can be explained as follows. First, all furnace sections like the heating, drawing, and cooling zone and their corresponding physical objects as for example a heating muffle need to be determined. Subsequently, these physical objects can be discretized into separate one-dimensional domains that can be coupled with each other using the fundamental laws of heat transfer. Depending on the number of interconnected discretized furnace sections, the final furnace length is determined. In the following, the furnace length is used to discretize two more one-dimensional domains, which are representing the furnace atmosphere and the steel strip. The just now discretized domains are also connected to the previously discretized furnace elements, resulting in an equation system that can be solved implicitly, creating the final implicit multiple one-dimensional approach.

The major difference between the proposed approach compared to CFD- simulations can be found in the massive reduction of simulation cells. Modern CFD- simulations regarding furnaces, rely on a fine three- dimensional mesh for which equations are solved for each spatial direction. Contrary to that the reduction into multiple one- dimensional domains only requires a solution into one direction which improves the computational time of a CFD case from weeks to minutes. It is important to mention that the results delivered by both methods cannot be compared with each other. CFD simulations provide a high level of detail, whereas reduced furnace models give a quick and approximate overview on the desired simulation parameters like the furnace atmosphere or product temperature.

Similar approaches are proposed by Steinboeck et.al., who modeled a slab reheating furnace utilizing the Galerkin method with heat radiation as only mode of heat transfer. [1] Another work showing the potential of simplified furnace models is given by Ganesh et. al. who first calculated the heat transfer within a four-zone separated furnace including the effects of austenitization. [2]

The purpose of this paper is to demonstrate the potential of implicit multiple one- dimensional discretization methods, which solves these coupled one- dimensional domains using an implicit formulation, to predict industry data and its corresponding speed advantage compared to CFD-simulations. The main objective is to model an indirect- fired heat treatment line, which heats an incoming steel strip and keeps it at drawing temperature. Subsequently, the furnace atmosphere is abruptly cooled down by a quenching process reducing the steel strip temperature significantly. (Figure 1) To show the model's capability, a test simulation case is generated and checked for plausibility.

Model structure

The simulation is developed using the programming and engineering software MATLAB® which provides highly developed solvers for linear equation systems. The code is structured in an object-oriented style consisting out of two furnace element objects, which can describe the true physical furnace elements. The first object represents a heating muffle that provides energy to the system. The second object is able to describe the drawing or quenching section, hence describing the furnaces physical counterparts of bridging or quenching elements.

To assemble the final furnace, a container object that requires the previously defined furnace element objects as an input is designed. The container object can take an arbitrary number of furnace element objects in any order, resulting in a very flexible method to design a heat treatment line. The provided input is afterwards used to automatically initialize the furnace atmosphere and steel strip discretization. Figure *1* shows a conceptual sketch of assembled furnace element objects, where notation M_i represents the muffle object, C_i, a bridging element and Q_i a quenching object that cools down the steel strip. (Figure 1)

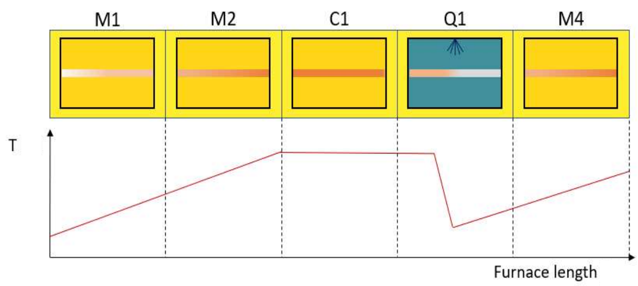

Figure 1: Conceptual sketch of assembled furnace objects

Geometrical discretization

As mentioned in the previous chapter, the model structure is divided into three different classes, providing member variables and functions to store and process data, respectively. Each object contains its own specific discretization method which is briefly described in the following three paragraphs.

The muffle furnace object requires several geometric input parameters that describe the major outlines of the real device including fireproof insulation as well as information about the burning chamber within the muffle object. The provided data is used to initialize a concentric shell-like structure, representing cell interface areas and radially increasing finite volumes. Furthermore, a subdivision into three different zones is executed in order to assign properties for the inner muffle insulation, the burning chamber that causes the energy supply and the outer muffle insulation.

The second furnace object, which can be used as a bridging or quenching element, needs similar input as the muffle object. The major difference can be found in the zonal subdivision, in which only one zone is required. This zone represents a continuous heat insulation, containing all information about the fireproof material. To distinguish between bridging and quenching objects another parameter needs to be defined. This is used to characterize the mode of operation that is subsequently used in the container object as a decision criterion to define a source term if operating as a quenching object or not.

Finally, by assembling the previously defined objects using the container object, the furnace atmosphere and the steel strip discretization is executed. Both, atmosphere and steel strip are discretized along the furnace axis utilizing the already initialized objects. The number of cells along the furnace axis can be controlled by an additional parameter that can be modified for each furnace element, respectively. By changing the number of cells per element along the furnace axis or using elements of different length, the step size between adjacent cells varies, causing numerical errors if not treated correctly in the solution algorithm. Therefore, the developed solver must take in account non- equidistant grid initializations. (Figure 2: dx)

A major advantage of the described discretization algorithm is its high flexibility towards changes of the simulation geometry. A fully automatic mesh generation of an industrial furnace can be initialized by defining a few parameters like cell count or geometrical dimensions, yielding results within seconds. In contrast to that, the meshing process for CFD cases can take up to several weeks depending on the geometry's complexity. Moreover, the applied algorithm arranges the discretized volumes in a structured way, which in return reduces the computational effort for the linear equation solver afterwards. Figure 2 shows a simple example of two discretized furnace elements, in which *OI is the outer insulation, *II the inner insulation, *FA the furnace atmosphere and *SS the steel strip.

Another insight shown in Figure 2 is the cells connectivity if considering the multiple one- dimensional approach. Heat can only be transferred along cells with the same cell discretization. More specifically, this means that cells, which for example represent the furnace insulation, can only transfer heat radially but not along the furnace axis, hence a communication between the muffle element insulation material and the bridging or quenching element insulation is not possible. This reduces the number of equations that must be solved significantly and increases the models computational speed. In principal, this assumption does not fit reality, but is almost true if the length of furnace elements as well as the thermal conductivity of the insulation material is small.

To transfer heat between the respective cell zones, neighboring cell zone values are used as boundary conditions for the possible mechanisms of heat transfer. A detailed description of the different mechanisms of heat transfer and their integration in the current model are given in the chapter "transport mechianisms".

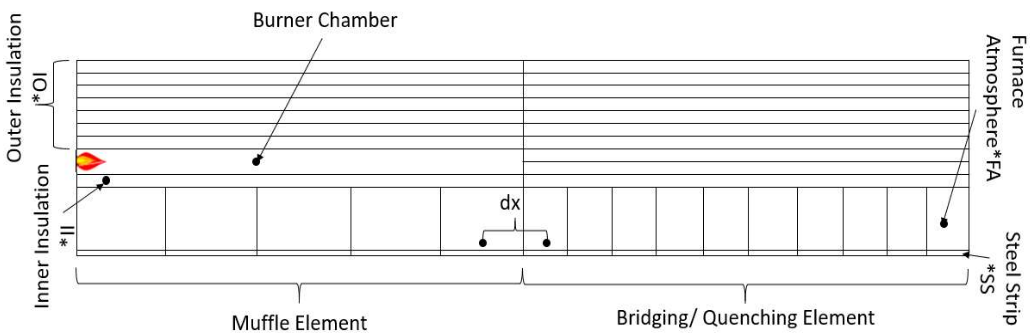

Figure 2: Discretization of upper cross section along furnace axis

Transport mechanisms

To implement the fundamental laws of heat transfer and apply them to the various cell zones, the respective discretization regions can be grouped together, yielding three main zones that can be described by the corresponding set of equations. All zones share the same basic mathematical concept by satisfying energy conservation as shown by the explanatory equation below, where Q_{acc} is the accumulation term, Q_{cond} the conduction term, Q_{conv} the convection term, Q_{rad} the radiation term and Q_{src} the source term for power, respectively.

$$Q_{acc} = Q_{cond} + Q_{conv} + Q_{rad} + Q_{src}$$

The first group consists of the radially discretized wall elements which are the initially defined furnace element objects provided to the container object. Depending on the exact object type the equation shown below varies regarding its source or sink term and the burner chamber radiation terms, respectively. All other terms generally describe the heat transfer by conduction, convection and radiation assuming constant and temperature independent thermophysical properties. The model used to describe radiation is a surface to surface model which utilizes view factors to determine the heat transfer from one surface to another. Although capturing a majority of the radiative heat transfer processes, the implementation is subject to a limitation due to the current calculation of the view factors. The current view factors only account for the radiative heat transport from the respective wall element surface to the steel strip surfaces within the same furnace element. This introduces an error since neighboring furnace elements have a significant impact on the radiative heat transfer. Another introduced simplification is the neglection of gas participation in the radiation process. This assumption is valid, because the simulated model represents an indirect- fired furnace with flue gas consisting entirely of nitrogen which is not relevant for radiation as would be for example other polyatomic gases like H_2O and CO_2. [4] The term $(h_e - h_a)\dot{m}_l$ shown by the equation below is specific to the muffle furnace element and describes the enthalpy provided to the system. The computation of both enthalpies, the in- and outflowing ones, are computed by the cheminformatics software package Cantera [3] that provides a MATLAB toolbox and offers powerful functions to solve chemical kinetics.

$$\begin{aligned} m_i c_p \frac{T_i^{n+1} - T_i^n}{\Delta t} &= -\frac{\lambda A_i}{\Delta d_i}(T_i - T_{i-1})^{n+1} - \frac{\lambda A_{i+1}}{\Delta d_{i+1}}(T_i - T_{i+1})^{n+1} \\ &- \alpha_i A_i \left(T_i - T_{(j,BC,atm)}\right)^{n+1} \\ &- \alpha_{i+1} A_{i+1} \left(T_i - T_{(j,BC,atm)}\right)^{n+1} \\ &+ 2\left(\frac{\sigma A_m \sum F_{i,k}\varepsilon_k}{\frac{1}{\varepsilon_i} - \left(\frac{1-\varepsilon_i}{\varepsilon_i}\right)(F_{ii} + \sum F_{ik}(1-\varepsilon_k))} (T_i)^{n+1}(T_i^3)^n \right. \\ &\left. - \frac{\sigma A_m \sum F_{i,k}\varepsilon_k}{\frac{1}{\varepsilon_i} - \left(\frac{1-\varepsilon_i}{\varepsilon_i}\right)(F_{ii} + \sum F_{ik}(1-\varepsilon_k))} (T_k)^{n+1}(T_k^3)^n \right) \\ &- C_s (T_i)^{n+1}(T_i^3)^n + C_s \left(T_j\right)^{n+1}\left(T_j^3\right)^n + (h_e - h_a)\dot{m}_l \end{aligned}$$

With m_i being the mass, c_p the heat capacity, T the temperature, Δt the time increment, λ the thermal conductivity, A the cell interface area, Δd_i the center to center distance, α the heat transfer coefficient, σ the Stefan-Boltzman constant, ε the emission coefficient, F view factor, C_s radiation coefficient, h_e incoming specific enthalpy, h_a leaving specific enthalpy and $\dot{m}$ the mass flux of burner gas.

The second set of equations required, describes the furnace atmosphere cell zone. The main transport mechanisms occurring in this zone are of a convective nature and characterize the heat transfer from the furnace and steel strip surfaces as well as the convective transport within the moving medium itself. The inclusion of diffusive terms was not considered in this approach since the thermal conductivity of the flue gas can be assumed low. The source term becomes relevant if the enclosing furnace element is defined as a quenching object. The assembling algorithm places a negative value, equivalent to the added cooling capacity, at the correct cell location. Therefore, both parameters, cooling capacity and global location must be defined in the quenching object before.

$$\begin{aligned} m_i c_p \frac{T_i^{n+1} - T_i^n}{\Delta t} &= v_i A_i \rho c_p T_{i-1}^{n+1} - v_{i+1} A_{i+1} \rho c_p T_i^{n+1} \\ &+ \alpha_{i,W} A_{j,w} \left(T_i - T_{j,w}\right)^{n+1} \\ &+ \alpha_{i,S} A_{j,S} \left(T_i - T_{j,S}\right)^{n+1} + Q_{src} \end{aligned}$$

With v being the velocity and $\rho$the density.

The last set of equations defines the energy transport in the steel strip cell zone. Compared to the furnace atmosphere zone the conductive terms cannot be neglected anymore due to the magnitudes larger thermal conductivity. The movement of the steel strip is modeled as a convective transport using the steel strip velocity as an input parameter. A source term is not implemented in the current model but can easily be added to describe chemical reactions and second order phase changes during the tempering process.

$$\begin{aligned} m_i c_p \frac{(T_i^{n+1} - T_i^n)}{\Delta t} \\ &= v A_i \rho c_p T_{i-1}^{n+1} - v A_{i+1} \rho c_p T_i^{n+1} \\ &+ \alpha_i A_j \left(T_i - T_j\right)^{n+1} - \frac{\lambda A_i}{\Delta d_i}(T_i - T_{i-1})^{n+1} \\ &- \frac{\lambda A_{i+1}}{\Delta d_{i+1}}(T_i - T_{i+1})^{n+1} \end{aligned}$$

All boundary conditions of the model are assumed to be of a Dirichlet type. This is implemented in the code by setting fixed temperature values at the boundaries of the model, representing for example the inlet process air temperature or the ambient temperature.

Implementation of equations

The equations defined in the previous chapter are implemented in a solution algorithm that sets up a coefficient matrix and a corresponding solution vector representing a linear equation system as shown in the equation below:

$$\boldsymbol{A}\, T^{n+1} = b$$

This is known as the implicit approach to express these equation systems which brings along several advantages that will be discussed in more detail. **A** is the so-called coefficient matrix containing the coefficients belonging to the unknown future temperatures, whereas b is the solution vector consisting of actual temperature and source terms. To calculate the latest temperature step, this linear equation system only needs to be solved for T^{n+1}, which can easily be done by MATLAB's automatic equation solvers.

The generation of the coefficient matrix **A** follows a structured approach that returns a well sorted matrix system as shown in the adjoining figure. This well sorted structure is based on the structured grid owed to the geometrical discretization process. A well sorted matrix has the advantage that the linear equation solver does not have to excessively pre-sort the respective equations, thus speeding up the solution.

Another inside that is given by the coefficient matrix is the cell connectivity. A strictly one- dimensional system would only have its matrix entries at the main diagonal and its direct neighbors, resulting in a tri- diagonal matrix. In this case there is a considerable amount of side diagonal entries which can be explained by the interconnection of the multiple one-dimensional domains. (Figure 3)

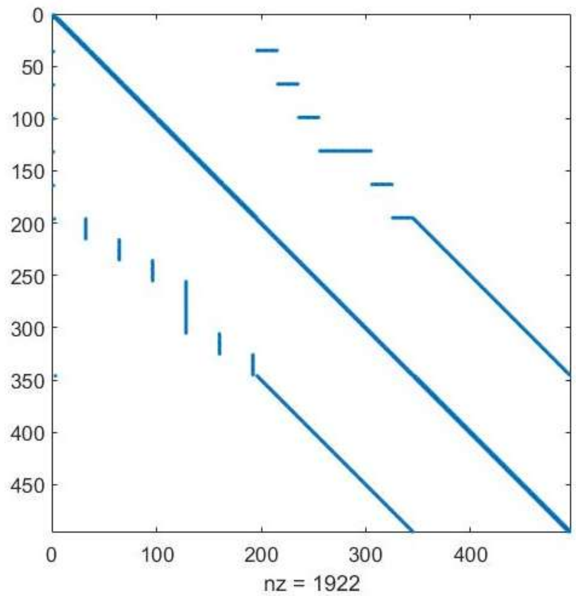

Figure 3: Structure of coefficient matrix representing a 500-cell model

The major reason for using an implicit approach to discretize and solve the equation system is because of stability reasons. Implicit solution methods are commonly known as unconditionally stable whereby the time increments, and grid size can be selected almost arbitrarily. Although, implicit schemes provide a high flexibility in regard of time increments and the grid size, dimensionless key figures like the Courant-Friedrichs-Levy (CFL) condition and the numerical Fourier number are of interest. Typically, the CFL condition should be below 1 whereas the numerical Fourier number should be below a value of 0.5 to assure the systems stability. [5] To honor these criteria a time step control is implemented in the code which calculates the maximal time step for a given condition and returns a warning if the selected time step is picked larger.

Results

As a proof of concept, a simple test furnace using literature values and a provided range of operating data from industry partners, was set up. Due to the lack of reliable measurement data, only quality checks for the heat treatment lines operating temperature could be used to check the results plausibility. The main boundary conditions used to setup the simulation case can be extracted from Table 1.

Table 1: Boundary conditions of simulation model

Process Air		
v	0.25	m/s
T	600	K
Steel Strip		
v	1	m/s
T	298	K
width	0.7	m
thickness	5	mm
Furnace		
length	30	m
No. of elements	12	
Inner height	0.75	m
Inner width	1	m
Heat transfer coeff.		
α_{W-A}	35	W/m^2K
α_{F-A}	35	W/m^2K
$\alpha_{Q(W-A)}$	1250	W/m^2K
$\alpha_{Q(F-A)}$	1250	W/m^2K

The furnace is built by twelve elements, each having an equivalent length of 2.5 m. The grid resolution along the furnace axis is generally twenty cells per element, except the quenching element where a finer resolution of 100 cells is selected. The number of cells to describe the complete insulation and burning chambers is 753, resulting in a total number of 1023 of cells.

The furnace setup was done by placing six muffle elements first to increase temperature followed by two bridging elements that hold the temperature approximately at draw temperature. Subsequently, a quench object cools the atmosphere and steel strip over a length of 0.75 m after which three muffle elements apply a stress relief heat treatment. The heat transfer coefficients characterizing the heat transfer between atmosphere/steel strip and atmosphere/ furnace wall are selected to be constant at 35 W/m^2K along the furnace axis, except for the quenching distance where significantly larger coefficients can be expected. Depending on the type of quenching process applied, the value of the heat transfer coefficient can be up to ten thousand W/m^2K whereas a process including water jetting was assumed. Processes of this nature have a large variation of the heat transfer coefficients since the droplet size, jet speed and amount have a large influence. Ultimately, a constant heat transfer coefficient of 1250 W/m^2K along the quenching distance was selected. [6]

The remaining parameters like thermal conductivity of the fireproof material or the respective heat capacities were selected using the VDI heat atlas. [7] The computed results using the above boundary conditions are in good accordance with the defined simulation case. First, the atmosphere temperature increases due to the primary placed muffle elements. As soon as the bridging elements are reached the atmosphere temperature drops which can be explained by the significantly lower bridging element wall temperature. In the vicinity of the quenching element the atmosphere temperature falls of sharply due to the cooling water jet. At the end, the atmosphere temperature increases again because of the following three muffle elements that provide energy for the stress relief heat treatment. Some noticeable unphysical characteristics are also visible in the furnace atmospheres temperature profile. More specifically, the discontinuous drop in the temperature profile as located at 17.5 m which corresponds to the transition from one bridging element to the next one. The explanation of this behavior is the limitation of the radiation model, only allowing the heat to be locally transferred but not globally. This causes a larger difference in temperature between adjacent wall elements than would be the case in reality. Ultimately, this leads to a difference in convective heat transport resulting in temperature abnormalities.

The temperature profile of the steel strip also shows an expected result regarding the associated furnace setup. The temperature rises to its draw temperature until it starts to stagnate when reaching the bridging elements. At the quench element, temperature drastically falls off again where it stays at its stress relief treatment temperature.

The real time operation period under consideration yielding the presented simulation results is 50,000 s (approx. 13.9 hrs) and starts from downtime. In order to generate them, it only took 51 s on an Intel i7- 8550U processor, showing the enormous potential to use this approach as a quick decision tool. A possible field of application would be as a support tool when designing new heat treatment facilities, allowing to make quick estimations of the resulting temperature profile for given operating parameters. Another, more involved approach for future applications would be the possibility to compute the required operating parameters like gas fluxes for a given heat treatment line and the required temperature profile of the produced product.

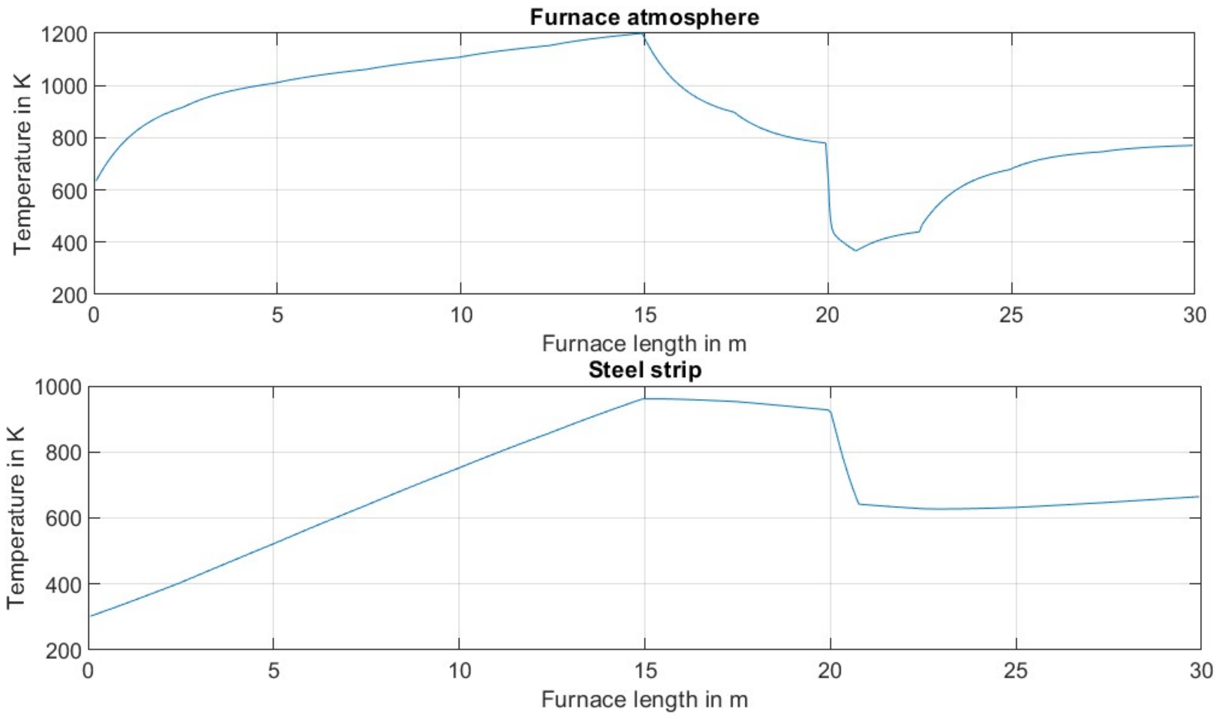

Figure 4: Temperature profiles of furnace atmosphere and steel strip at the end of simulation

Outlook

As proven by the previous chapter, using the implicit multiple one- dimensional finite volume approach to research reduced furnace models is a powerful tool. Interesting future work would be the improvement of the model description in regard of the radiation model's capability to determine global heat transfer and the further increasement of the model's functionality by implementing prediction tools to estimate the temperature effect on the heat-treated products. Further improvements can be implemented by replacing the constant assumed coefficients with temperature dependent correlations.

To increase the applicability of the furnace model, different heating strategies can be implemented as for example electrically heated muffle elements. Similarly, different cooling strategies like nozzle fields instead of water jets can be realized to make the quenching objects more flexible.

Apart from improving the model's accuracy and flexibility, the utilization of already implemented transport mechanisms can be used to calculate heat losses of a specific simulation setup and region. Therefore, this feature would provide the possibility to compare different furnace setups, making optimizations in regard of energy consumption possible.

Subscript

i .... Current cell
j .... Neighboring cell in convective term
k .... Neighboring cell in radiation term
BC .... Burning chamber
atm .... Furnace atmosphere

Superscript

n .... Current time step
n+1 .... Time step ahead

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