Sustainable Thermal Processes for Shaped Refractories through Digitalization

G. Seifert, H. Ziebold, H. Friedrich

To remain competitive in a climate-neutral future with energy supply based on regenerative sources, the production of refractories and ceramics in general has to be transformed to a considerable degree of digitalization. Future kiln control systems should contain enough knowledge in digitized form about the product material's behavior in the thermal process to enable automatized flexible use of the cheapest appropriate energy (due to fluctuating supply) at any time. On the way to this functionality, digital furnace twins can be a key tool to virtually develop the new thermoprocess equipment tailored to the needs of a product material and the expected local energy supply options. For an immediate benefit, already available mature digital thermoprocess models can be applied to considerably reduce the energy consumption of existing production processes by systematic computerized optimization.

1 Introduction

The European Green Deal with its ambitious goal to bring the net CO_2 – or more general greenhouse gases – emissions in the EU to zero until 2050 creates an increasing pressure particularly for the energy-intensive industry to increase the sustainability of their production processes continuously over the next 25 years. This is apparently also a crucial issue for refractory producers as to the necessity of firing refractory bricks and many other shaped products at temperatures above 1000 °C, which today is mostly done in large kilns heated by combustion of natural gas. The imminent transformation of the European industry into a climate neutral one implies for the producers of shaped refractories to convert their production, in particular the most energy-intensive thermal processes, step by step into the economically and ecologically most effective new concept based on regenerative energy sources.

To manage the challenge of this unavoidable transformation without losing competitiveness, well-balanced activity on different time scales appears appropriate: during the next years, the priority is clearly on optimizing the process efficiency within the existing thermoprocessing equipment. On the long run of, roughly, 10 to 20 years a redesign or complete replacement of the equipment will in most cases be necessary. The challenge in this context is, besides the obvious problem of acquiring the financial freedom to make the investment, to safely identify the most appropriate technical concept for one's specific products.

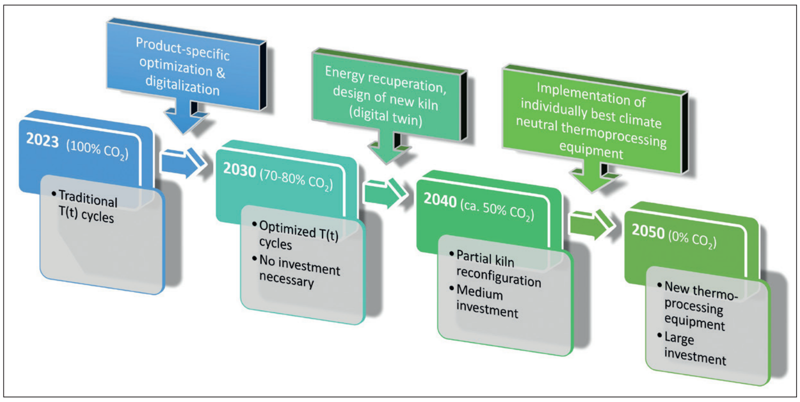

Fig. 1 Schematic overview of a possible scenario to stepwise reduce the carbon footprint of existing thermoprocessing equipment.

Fortunately, thermal process modelling and further digital technologies are developed far enough to be able to assist the refractory industry in the above-mentioned process optimization on the short term as well as in making informed decisions on the future renewal of their thermal processing equipment. Fig. 1 presents a schematic overview of a possible scenario to stepwise reduce the carbon footprint of existing thermoprocessing equipment culminating in a, probably in most cases necessary, complete replacement of the kiln by a new, technologically different system towards 2050.

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Of course, the timeline given in the Figure is only a rough estimation for an average pathway to carbon-free production, depending on the age and technical standard of the thermoprocessing equipment being currently in use.
In this article, the methodologies established at Fraunhofer Center of High Temperature Materials and Design HTL for identifying the best solutions on this individual pathway will be outlined.

2 Material-specific thermal process modelling

Future-oriented kiln plant providers are nowadays developing their kilns towards higher energy efficiency by implementing various constructive improvements such as advanced insulation materials, heat recuperation or advanced furnace control based on sensors monitoring continuously key performance parameters like temperature and pressure at numerous positions throughout the kiln. The latter is apparently a prerequisite for further digitalization including fully automatized control of thermal processing procedures.
Usually this redesign for progress in energy efficiency is done from a bird eye`s view, i.e. the flows of energy into, within and out of the kiln plant are considered, but mostly no specific measures are taken to adapt the thermal process parameters specifically to the needs of the products. Such a material-specific view, however, has a great potential to reduce the energy consumption per product by typically up to 20 % without the need for any investment into the equipment, just by goal-oriented modification of temperature cycle and, possibly, firing stack setup. This potential stems from the often – with respect to energy efficiency – poorly optimized thermal cycles, which have been designed empirically with in doubt slower heating and cooling rates and longer dwell times than would be ideally possible. Such suboptimal thermal process parameters are usually a consequence of the demand to be on the safe side what concerns component damage during heat treatment or to keep the condition that even the component at the most unfavorable position within the firing stack undergoes the required peak temperature for a long enough period of time.
Fraunhofer HTL has developed versatile experiment-based finite element (FE) models for drying, thermal removal of organic components [1] and for sintering [2], which enable detailed analyses of the behavior of arbitrarily-shaped components during the thermal process on the computer. Using material-specific precise in-situ measurements, these models are able to predict reliably the progress of drying or debinding through the volume of a component as well as possible shrinkage or further deformation effects during sintering. Possibly deleterious effects with respect to component damage such as internal pressure in the bulk of a product due to emanating gases or critical tensile stresses caused by steep temperature gradients can be assessed in detail in the simulations.
In the first iteration this assessment can be done on the basis of the established temperature cycle: in this case, the peak stresses occurring during the thermal process are calculated as a reference. Thereafter, modified temperature cycles for higher energy efficiency are developed on the computer iteratively such that the "allowed" maximum reference stresses are not exceeded. With the prerequisite of more experimental effort also a more advanced approach of the material-specific limits is possible. E. g., when the strength as a function of debinding or sintering status is known from a series of fracture experiments on samples in different process states, one can exploit the full potential for a faster and more efficient

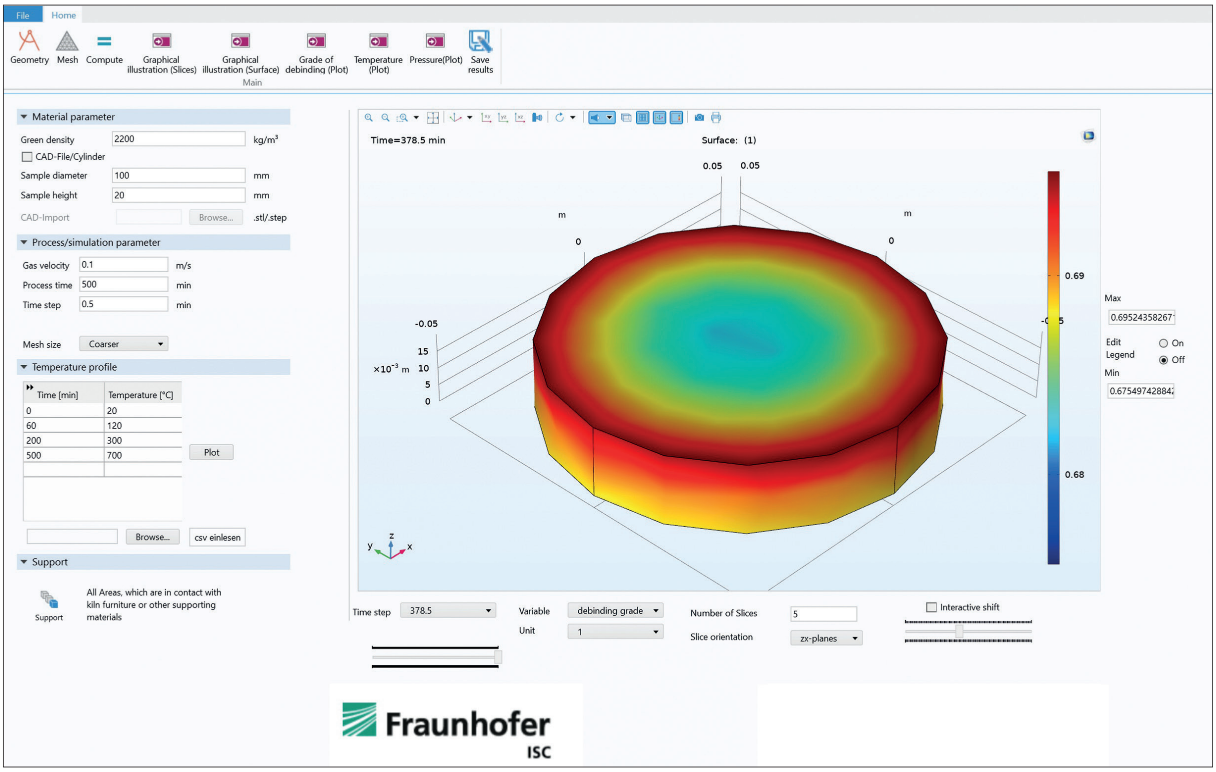

Fig. 2 Screenshot of User-App for the optimization of thermal debinding process.

thermal cycle (because the established, empirically defined cycles are often in many phases far away from that limit). Currently under development is an automatized optimization routine utilizing AI algorithms to identify independently the most energy-efficient thermal process parameters [3]. Validation of the optimized thermal cycle is possible in one of the specially developed ThermoOptical Measuring systems at Fraunhofer HTL (TOM_wave [4,5]) by monitoring in situ during the heat treatment the acoustic emission coming unavoidably with crack formation. By help of such experiments, the maximum heating (and cooling) rates derived from the FE model can be validated before the modified temperature cycle is transferred to the production furnace.

The optimization technique has in the last years been successfully applied to various industrial thermal processes, mostly in the field of ceramics production. Owing to the demand from industrial project partners, Fraunhofer HTL has established an option to provide the thermal process modelling in form of standalone user Apps. Based on the functionality of the commercial FE software COMSOL and an initial set of measurements to acquire the user-specific material data necessary to fully characterize its behavior in the thermal process, software tools for material-specific thermal process optimization with different degree of detail [1] can be tailored to the needs of the industrial user. The advantage of this concept is that the industrial user of the material-specific App does not have to disclose operational details, but can perform the process optimization on his own. Fig. 2 shows as an example a screenshot of an App compiled for optimization of a debinding process.

3 Model-based efficiency enhancement in existing kilns

The technology for determining the optimal parameters for energy efficient thermal treatment, as far as outlined in the previous chapter, accounts for any material- and component-specific aspects. I.e., for well-defined boundary conditions of heat transfer to all surfaces of the refractory component, an optimal temperature cycle can be identified which ensures that the intended final state of the material is achieved throughout the volume of the component with minimal energy consumption. For a transfer of this T(t) curve to the real production furnace, apparently the effects of the actual firing stack setup have to be regarded. While in some simple cases (low packing density of components in furnace, slow heating rates) the FE model of a single component may be a sufficiently good approximation for all components in a stack, the majority of firing processes, in particular for refractories, is performed using densely packed products both for economical and energy efficiency reasons.

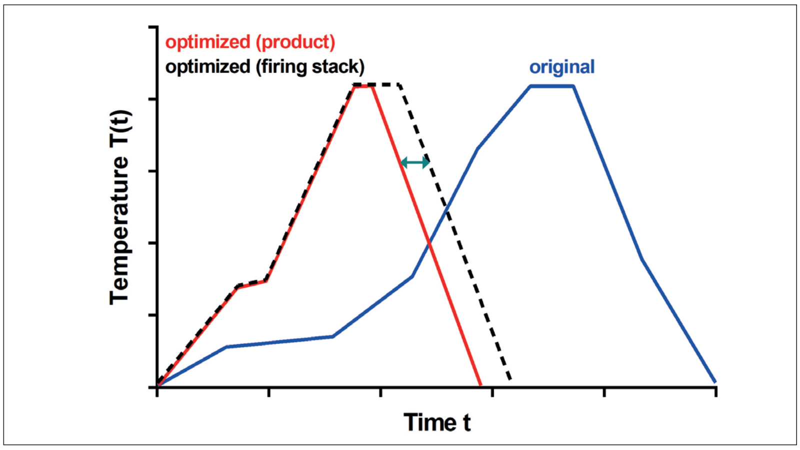

Fig. 3 Schematic sketch of potential for reduction of total time (and energy consumption) for thermal cycles in refractory production.

To account for the impact of a firing stack on the heat transfer processes, with the most prominent effect of delayed heating in the center of the stack, experimental as well as simulative approaches can be successfully applied. An obvious experimental method to acquire the necessary information is to place thermocouples in the interior of a firing stack, usually with appropriate wire connection to a temperature recording system outside the furnace. Another option are appropriately positioned autonomous, well-isolated boxes recording the local temperature (and optional further parameters like pressure) during the whole thermal cycle for readout after the process is finished. An advanced version of such a high temperature sensor box, which will be able to withstand a complete run through a continuous furnace, e. g. a gas-fired tunnel kiln, of up to 24 h has been developed and is currently in the test phase at Fraunhofer HTL [3]. With respect to thermal process optimization, the key information to be obtained from such temperature recordings is the delay of temperature increase in the center of the firing stack compared to the preset temperature T(t) of the furnace control system. Knowing this delay, the previously optimized temperature can be modified to account for spatial effects in the firing stack; it is an obvious approach to prolongate the dwell time at maximum temperature by the measured time delay. While this provides a reasonable approximation to achieve the precalculated optimal temperature cycle for the products in the center of a firing stack, the necessary extension of the overall T(t) curve in the kiln reduces the gain of efficiency with respect to the previous original cycle, as exemplarily illustrated in Fig. 3.

The simulative approach to analyze the heat transfer within a firing stack can basically provide the same information as the above-mentioned experiments, but has additionally great potential to understand much more details about the local thermal situation and accordingly exploit further options for optimization. To keep the computational effort for FE and CFD (computational fluid dynamics) modelling of a firing stack manageable, one describes such a stack, whenever possible, as homogenized block of material with effective thermal parameters (utilizing the mostly present periodicity). A schematic representation of such a multi-scale simulation concept is shown in Fig. 4 for an exemplary firing stack on a kiln car (e.g., in a tunnel furnace). For geometrically simple cases like bricks one can often also use analytical expressions for effective thermal parameters [6]. The benefit of the modelling is that the delayed heat transfer to a component in the middle of the stack can not only be simulated for the actual implemented stack setup, but also for modified,

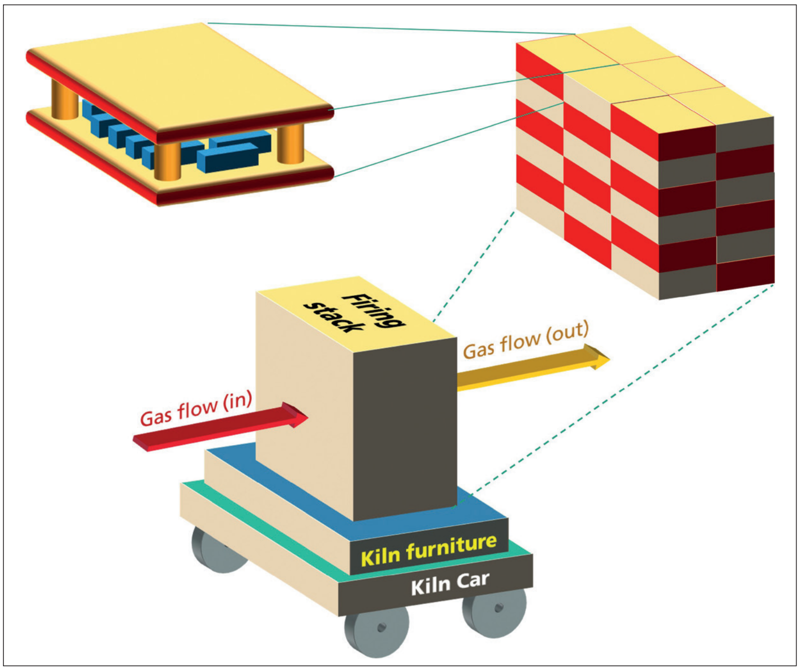

Fig. 4 Schematic sketch of multi-scale representation of firing stack in FE model.

potentially more efficient situations. For instance, one can study if lower packing density of the products or different supporting elements or, if the kiln allows that changes, higher gas velocities could be beneficial in the sense of shorter and more efficient thermal cycles.

This upscaling of the material- and component-specific thermoprocess models can also be provided in form of COMSOL user Apps for independent use. Pertinent concepts to model the individual situation regarding furnace conditions and firing stack setup in an effective way have been (and are still being further) developed by Fraunhofer HTL in a current funded research project [3].

A different approach to increase productivity (and thus reduce the energy consumption per product) without the need for considerable investment in the thermoprocessing equipment is the analysis of large amounts of production data to identify kiln-related sources of scrap in the process output. While this approach requires a sufficient degree of digitalization of the thermoprocess, in particular enough sensors throughout the production kiln, it is also feasible for cases where the above-described, material-centered approach is not perfectly suited: e.g., for products having no or very small sinter shrinkage, or when products made of slightly different materials are fired together in the same furnace process. The approach requires a sufficiently large amount of production data, typically recorded over several weeks to grasp any possible parameter fluctuation. If such data are available and contain furnace parameters correlated to the production quality of – ideally – individual products or at least of groups of products having been fired on the same kiln car, modern data analysis (AI) algorithms are able to identify automatically critical process situations. Based on these findings measures can then be taken to prevent similar situations by appropriate modifications of the furnace control system, or – depending on the type of products – by optimized placement of the products on the kiln furniture / kiln cars etc. The latter is of particular importance for large and geometrically complex products, as is currently being demonstrated in a joint R&D project on the example of ceramic sanitary ware [7]. Corresponding products in the field of refractories could for instance be special kiln furniture. In general, however, the data-based approach is feasible for any kind of product requiring high-temperature processing.

4 Digital twins of future kilns as aid for investment decisions

The methods to improve the error-free output and the energy efficiency of a thermoprocess described in the previous chapters can be implemented within a few months or less depending on the complexity of the individual process. Usually only the parameters of the thermal process have to be modified for energy savings of 10–20 % or more and, in particular, no investment in the equipment is needed. Also, the costs for analyses and optimization are typically remunerated by the reduced fuel cost savings within half a year or less.

While this kind of process optimization apparently is an aid to remain competitive over the next few years, it can principally not reduce the energy consumption and CO_2 emission far enough to match the political goal of climate neutrality until 2050. To achieve this ambitious goal, refractory producers will – like any other industry requiring high temperature processing – mostly have to redesign their thermoprocesses and need to invest in new kiln technology. Main goals of such a reconfiguration are minimal total energy consumption in the company and the ability to produce with heat derived from regenerative energy sources. Besides several apparent measures like energy recuperation within the furnace and from the furnace to general purposes like office heating, the optimal choice for a new kiln system should include the fundamental decision about the heat source. As the main energy source of the future will – at least in Europe – be electrical power derived from solar or wind-driven power generators, one can expect that direct electrical heating will then principally be the most economic variant. Green hydrogen and in particular more advanced Power-to-Gas products such as ammonia or methane will, due to considerable conversion losses, be definitely more expensive.

Accordingly, any decision about new kiln systems has to consider several factors, which must be weighted for any individual case in a tradeoff between economic aspects and technical necessities such as heat transfer rates and composition of furnace atmosphere needed for the special material under consideration. For instance, even if one "only" wants to transfer a gas-fired kiln from natural gas to green hydrogen as new fuel, different effects have to be considered:

- To achieve the same heating power, much higher flow rates of hydrogen are required with the consequence of higher gas convection within the kiln. Depending on kiln construction and firing stack setup, this

may be either beneficial providing faster heat distribution and more homogeneous temperature or detrimental creating higher temperature gradients.
- The furnace atmosphere upon hydrogen combustion does not contain CO_2 any more, but much more water vapor than in the case of methane; this will apparently affect the thermodynamic situation – e.g., wanted reactions may be suppressed or unwanted reactions be fostered, leading in the worst case to a total failure of the thermal treatment.

For the more fundamental change from gas-fired to electrically heated kilns, more aspects have to be included: Basically, such a change brings flexibility for the furnace atmosphere (limited, however, by the material of the heating elements), but also additional costs for its external supply; similarly, the necessity for active ventilation causes additional cost for furnace construction and operation, but enables flexibility to tailor the convection to the needs of different temperature ranges.

In addition to these and much more product- and material-related questions, the future kiln system should be able to provide a demand-side management, i.e., take economical advantage of low energy prices in phases of large (and thus cheap) supply. This requires a thorough knowledge of one's specific heat treatment processes which ideally should be implemented in the furnace control so that it can automatically decide for how long excess power can be used or reduced heating rates are acceptable without the danger of corrupting the products in the furnace.

In order to make the right 'pinpoint' decision about the selection of a new kiln system for CO_2-free refractory production, it would be ideal to test and assess the performance of several potential concepts in advance. While this is apparently not possible on real kiln systems (which in many cases have not yet been practically realized at all), it is nowadays possible to set up digital twins of the different concepts in the sense of a virtual construction. In particular when they are coupled to the material-specific process models as described in the previous sections of this paper, the digital furnace twins can be used to evaluate the performance of a future-oriented technical kiln concept in advance on the computer. An effective method for such a coupling of material-specific thermoprocess models and thermal kiln model has recently been developed by Fraunhofer HTL [3]. Fig. 5 illustrates how this concept works: while in the model of a tunnel kiln segment a virtual kiln car loaded with several products (here ceramic wash basis) is moving along the furnace (background image of half tunnel kiln segment), the thermal transfer rates to the products are calculated for every time step. With this input, the heating and successive sintering compaction of the porcelain material is simulated (intermediate state of density distribution shown foreground image), and finally the outer temperatures are coupled back to the furnace model.

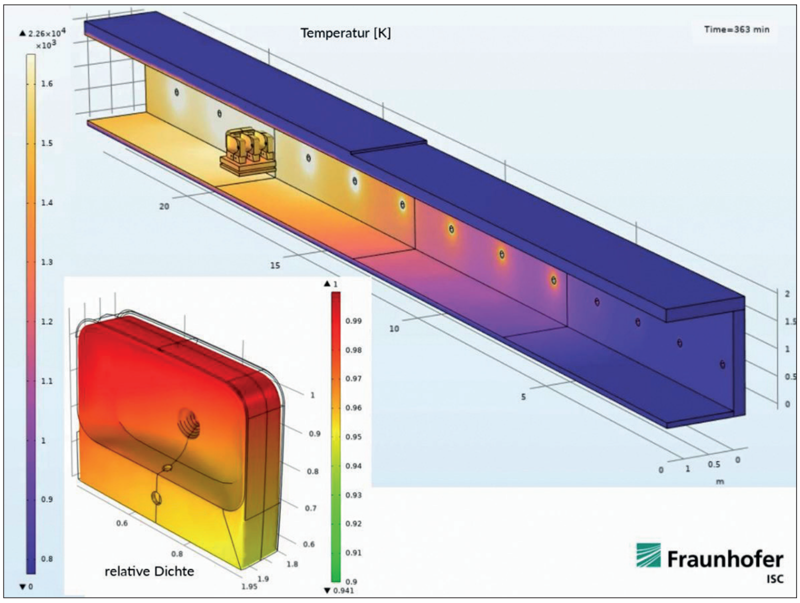

Fig. 5 Illustration of a sinter FE model of a large ceramic component (wash basin) coupled to the thermal model of a tunnel furnace segment (only one half shown).

A current research focus lies on the qualification and validation of the digital furnace models in order to systematically secure the precision required to make reliable predictions on the performance of future kiln systems, which are not yet existing in reality (not even in a demonstrator or prototype status). Digital furnace twins with the implemented knowledge about the material behavior in the thermal process would be an ideal tool to be included in the control system of future kilns for an automatized management of fluctuations in the external energy supply or prices. To meet this requirement, the digital twin must provide a reliable answer to external changes within seconds – this is not possible with direct solving of the FE and CFD models described above, which need computation times of minutes to hours or even days (depending on complexity of kiln and firing stack). Instead, one can create in advance a database of model solutions for various temperature cycles and further variation of thermal process parameters, and then compile so-called reduced order models from the database, which provide almost instantaneously the answers required for the kiln control system. This technology is also currently under development at Fraunhofer HTL [3].

5 Conclusions and Outlook

Today a collection of digital technologies are available for systematic minimization of the energy consumption and CO_2 emission of various production processes requiring high temperature firing. In particular, the material-centered approach of Fraunhofer HTL combining in-situ characterization and FE process modelling is ready and well-suited for immediate application to any kind of refractory products. User-specific apps can be compiled to enable an industrial user to optimize their thermal process parameters including the firing stack setup independently.

While this approach, which has an average potential for 10–20 % energy and cost reduction on the short term, works without modifications of the kiln hardware, the long-term goal of climate neutrality will usually require considerable investment in new thermoprocessing equipment. Digital Twins of the future furnace systems, which can help to make the correct investment decision, are already under development and will soon be available to full extent. With these digital representations of the projected kiln systems, nearly all relevant design questions can be conveniently answered - from the basic decision of electrical or combustion-based heating to details like the layout of heating elements or optimized dimensioning of hot gas ventilation. In addition, the simulations considering the specific material properties of the firing products are not only a tool for the planning phase, but can later (in the form of fast "reduced" models) be implemented in the furnace control system to enable flexible operation accounting for a fluctuating energy supply.

Acknowledgement

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