Model-based control and optimization of continuous strip annealing furnaces

by **Martin Fein, Michael Böck-Schnepps, Stephan Strommer, Martin Niederer, Andreas Steinboeck, Andreas Kugi**

The so-called ANDRITZ Advanced Furnace Control concept is used to control a combined direct- and indirect-fired strip annealing furnace of voestalpine Stahl GmbH, Linz, Austria. The backbone of this concept is a nonlinear model predictive controller for the strip temperature developed by ACIN, TU Wien. The controller is based on a computational efficient model that captures the most important nonlinear effects of the considered furnace. The controller additionally maximizes the throughput and minimizes the energy consumption. The capabilities of the proposed concept are demonstrated by a simulation study.

In the steel industry, annealing furnaces are used to control the material and surface properties of steel strips by means of heat treatment. Continuously increasing demands on the product quality are a challenge for strip temperature control. To achieve the desired product quality, the strip has to be heated according to a predefined temperature trajectory. However, due to the high thermal inertia of the furnace, the very few temperature measurements, and an ongoing diversification of product portfolios, heating is a demanding control task, especially in transient furnace operations.

A reasonable control concept for the strip temperature that facilitates the consideration of all these challenges is model predictive control. It is suitable for complex nonlinear systems such as annealing furnaces and it allows incorporation of secondary control goals like the maximization of the throughput, the minimization of energy consumption, and the minimization of CO_2 emissions. Because these control goals can be antagonistic, they are weighted in the optimal control problem according to their importance.

The basis for model predictive strip temperature control is a computational inexpensive mathematical model of the furnace that captures the most important nonlinear effects. Since a model-based control concept requires information of all system states, the furnace model is also used as a basis for a state observer. These building blocks, i.e., the furnace model, the controller, and the state observer, are assembled in the ANDRITZ Advanced Furnace Control (AFC) concept that is described in more detail in the following sections.

In this paper, the proposed control concept is presented for a combined direct- and indirect-fired strip annealing furnace of voestalpine Stahl GmbH, Linz, Austria (cf. **Fig. 1**). Inside the direct-fired furnace (DFF), four heating zones (HZs) each equipped with gas-fired burners are installed. In each HZ, natural gas is burnt in a fuel-rich combustion process in order to avoid oxidation of the strip. Therefore, the hot flue gas contains harmful products which are oxidized in a post combustion chamber (PCC) by adding fresh air. The heat that is released in this post-combustion is used for preheating the strip in the preheater (PH). The strip is mainly heated by the hot flue gas by radiation and convection. Finally the flue gas streams towards the funnel where the remaining energy is utilized for preheating the combustion air by means of a recuperator. The indirect-fired furnace (IFF) features an inert gas atmosphere and is split into a heating section (RTH) and a soaking section (RTS). Each of these sections is equipped with W-shaped radiant tubes that are combined to several heating zones. Inside a radiant tube, natural gas is burnt in a fuel-lean combustion process. In the IFF, the strip temperature is thus controlled by the surface temperature of the radiant tubes.

ADVANCED FURNACE CONTROL

The AFC consists of the modules observer, model predictive control (MPC), trajectory planning, and an optional

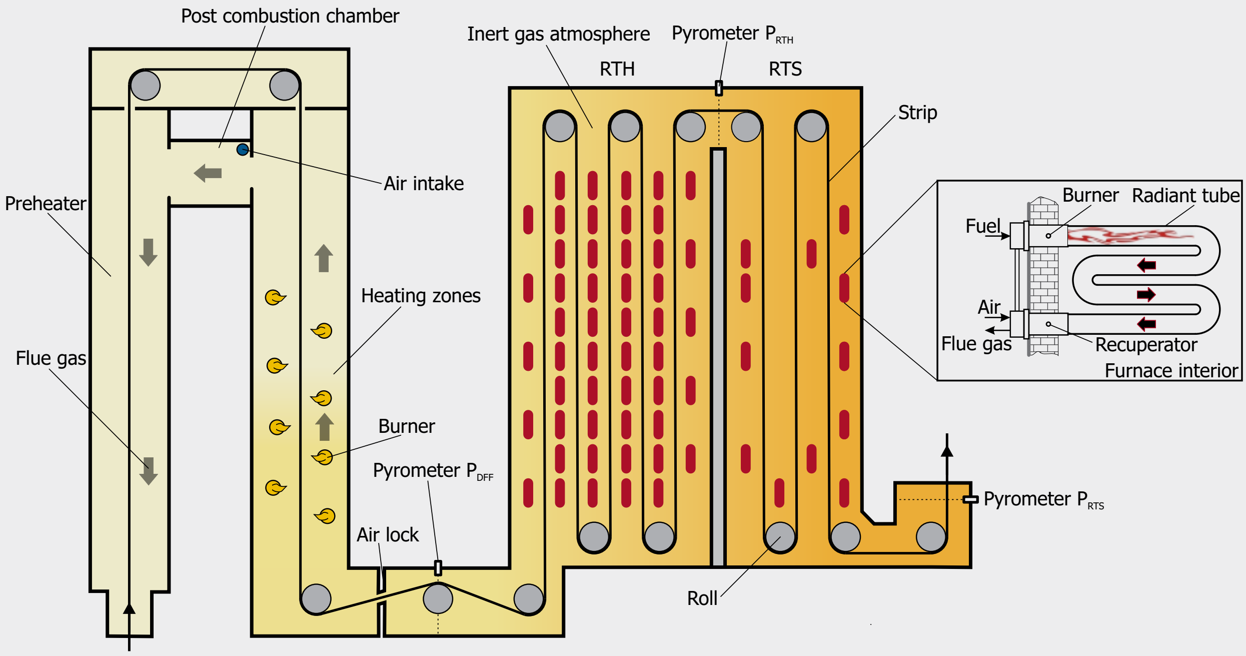

Fig. 1: Combined direct- and indirect-fired strip annealing furnace

offline simulator. The basis of the AFC is a computational efficient mathematical model consisting of submodels, which accurately capture the thermal behaviour of the furnace. The submodels are based on first principles, where the mass flows of fuel and the strip velocity constitute the system inputs. This approach results in a flexible and scalable design and allows the transfer of this model to other furnaces, e.g., stainless steel annealing furnaces or slab reheating furnaces.

The model-based observer estimates the actual temperature distribution by means of measured temperatures and system inputs. Moreover, unknown parameters can be estimated by the observer.

The operator may influence the process via the trajectory planning module. Here, target trajectories of the strip temperature and limits for the system inputs have to be specified. The trajectories and limits are required by the MPC module.

In the MPC module, a nonlinear dynamic optimization problem for a combined DFF and IFF is solved according to the specified control goals. The main goal is optimal strip temperature tracking. Furthermore, secondary goals as the maximization of throughput and the minimization of energy consumption, CO_2 emissions, and operating costs can also be taken into account.

The offline simulator module contains the mathematical model, the observer, the trajectory planning, and the MPC. In this application, the mathematical model constitutes a simulator of the furnace. The offline simulator can be used to determine an optimal coil sequence and is suitable for furnace operator training. Here, the influence of varying limits of the system inputs, which are adjusted by the operator, can be analysed. Furthermore, new products and heat-up curves can be verified offline in advance. The offline simulator can also be used to design new furnaces, to plan the revamping of existing plants, and to do energy analyses.

Fig. 2 shows an overview of the considered hierarchical structure of the furnace automation system, which consists of four levels. The AFC is located in Level 2. Level 0 contains sensors, e.g., thermocouples and pyrometers, and actuators, e.g., burners and electrical drives. The programmable logic controller (PLC) located in Level 1 receives the measured signals and includes the subordinate controllers for the actuators. Moreover, the PLC takes care of the material tracking and supplies the observer with measured process values like strip temperatures, mass flows of fuel, strip velocity, and the tracking information of actual and future coils. The actual states and the tracking information provided by the observer are used by the MPC. Based on these parameters and the mathematical model, the MPC determines optimal system inputs. These optimal values are the reference trajectories for the subordinate controllers. The optional module offline simulator is connected to the planning system located in level 3.

Traditionally, recipe-based control strategies are applied in the considered furnace. The recipes are identified during the commissioning of the plant, which is a sophisticated identification task. Moreover, so-called dummy coils are necessary to handle transitions in terms of material parameters, e.g., target temperatures. Here, AFC is useful because the time required for commissioning can be reduced significantly due to the nonlinear model. Additionally, dummy coils can be saved due to a precise strip temperature tracking.

By considering the temperatures calculated by the furnace model, additional optimization goals can be taken into account. For instance, target strip temperature can be specified at locations where no pyrometer is installed. Furthermore, damaging the furnace by overheating can be prevented by analysing temperature limits and temperature gradients, even if no temperature measurements are available. Moreover, the probability of the occurrence of heat buckles and snaking can be minimized by limiting the difference between the strip and the roll temperature [1]. In **Fig. 3**, this difference is illustrated by the green bars.

Modern furnace control concepts as AFC are fully in line with the Industry 4.0 paradigm because more information of the underlying process can be extracted. State-of-the-art visualization together with touch-based user input control facilitates an easier handling of the process for the operator. The visualization, e.g. on tablets (cf. **Fig. 4**), can be used to get detailed process information throughout the plant. AFC enables a full-automatic furnace operation and supports the operators to increase the product quality. By means of the visualization and the AFC, the operator obtains information of predicted temperatures used in the model. Quality data like the heat-up curve (cf. Fig. 3) can be integrated in any kind of data mining and analysis system.

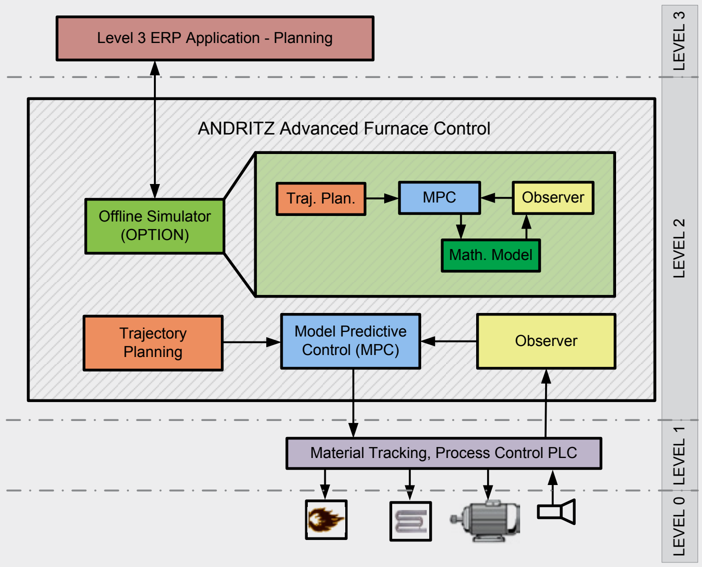

Fig. 2: Hierarchical structure of the furnace automation system

MATHEMATICAL MODEL

The mathematical model consists of individual submodels for the combustion, the flue gas, the radiant tubes, the rolls, the strip, and the wall. As indicated in **Fig. 5**, these submodels are interconnected by the heat transfer mechanisms.

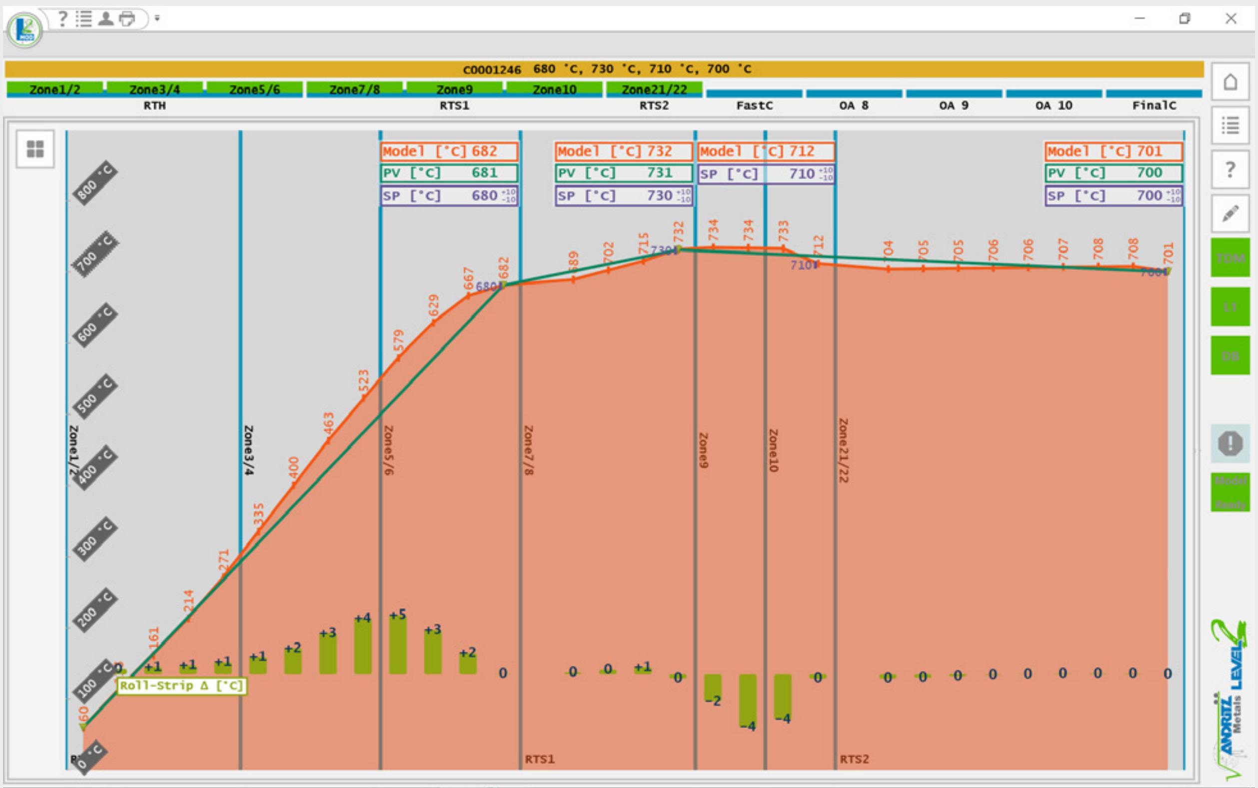

Fig. 3: Screenshot of a heat-up curve from the AFC application

Fig. 4: Tablet for on-site visualization

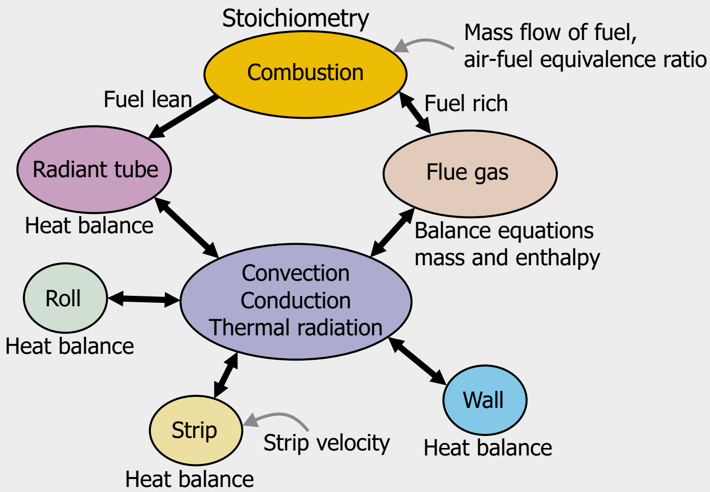

Fig. 5: Individual submodels of the strip annealing furnace

Moreover, the impact of the combustion of natural gas on the flue gas and the radiant tubes is indicated. A detailed description of the furnace model can be found in [2-4]. In the following, the mass flow of natural gas and combustion air and the strip velocity are used as control inputs.

The DFF is discretized into a finite number of volume zones. The combustion of natural gas inside a single volume zone is modelled by chemical reaction equations in order to determine the combustion products and the released energy. The flue gas is characterized by the composition, the total mass, and the temperature. The total mass and the outgoing mass flows of a volume zone are determined by the mass balance and the ideal gas law [4]. In the composition model, the mass balance for each component is considered. Moreover, the water-gas-shift reaction is utilized to model chemical equilibria. The flue gas temperature is determined by the enthalpy balance. The flue gas interacts with surrounding surfaces via convection and thermal radiation.

In the IFF, the fuel-lean combustion of natural gas occurs inside W-shaped radiant tubes. The resulting flue gas composition and combustion energy follow from a stationary mass and enthalpy balance. The combustion energy is transferred through the radiant tube wall into the furnace interior and is used to heat the strip by thermal radiation.

The strip is guided through the furnace by means of rolls. The dynamic behaviour of the strip temperature is modelled by heat balances, i.e., the strip temperature is considered homogeneous along the width and thickness of the strip. Moreover, heat conduction in the longitudinal direction is neglected due to small temperature gradients. Heat balances are also used for modelling the roll temperatures. The heat exchange between the strip and the rolls is modelled by conductive heat transfer [5].

The dynamic behaviour of the wall temperature is governed by one-dimensional heat conduction. Based on the heat conduction equation, a low-dimensional and computational inexpensive lumped-parameter model of the wall temperature is derived using the Galerkin method [6].

Thermal radiation is the most important heat transfer mechanism in annealing furnaces due to the high temperatures. In the considered furnace, the zone and the net radiation method are utilized for calculating the heat exchange by radiation [7]. Both methods require the computation of so-called direct-exchange areas [8]. Additionally convection is considered in the DFF between the flue gas and its surrounding surfaces and is described by Newton's law of cooling [9].

Using the singular perturbation theory [10], the assembled furnace model can be represented by a nonlinear differential-algebraic state space system. Because not all parameters of the first-principles model are precisely known, some are determined by parameter identification [3-4]. For time integration of the model, the Courant-Friedrichs-Lewy condition which defines a nexus between the sampling time, the strip velocity, and the spatial discretization of the strip has to be satisfied [11].

The furnace model is verified by a comparison of simulation results with measurement data from the real plant. **Fig. 6** shows the strip temperatures at the three pyrometer positions P_{DFF}, P_{RTH}, and P_{RTS}, cf. Fig. 1. These results indicate the high accuracy achieved by the mathematical model.

MODEL PREDICTIVE CONTROLLER AND STATE OBSERVER

The main goal of AFC is that the strip temperature is controlled to a target temperature or temperature range. In the presented AFC, this control task is solved by means of nonlinear dynamic optimization in form of a model predictive control concept. Here, both the mass flows of fuel and the strip velocity are used as optimization variables.

Based on the properties of the considered furnace, a tailored optimization problem and a corresponding solution algorithm are used. The furnace model is normalized using a nonlinear time transformation that depends on the strip velocity. This ensures that the strip length considered in an MPC horizon is constant.

To meet the different control goals, a tailored objective function that depends on the system inputs and states is defined. Constraints of inputs and system states are systematically taken into account by using sigmoid functions and additional penalty terms in the objective function. The discrete-time optimization problem (objective function and furnace model as equality constraint) is iteratively solved by means of the Gauss-Newton method [12]. The required gradient vector and the (approximate) Hessian matrix of the objective function can be analytically computed.

The iterative solution of the optimization problem requires the repeated evaluation of the objective function. This is why an efficient time integration scheme that enables large time steps with a minimal loss of accuracy is used. Thus, the repetitive calculation of the model is accelerated and the time needed for the solution of the optimization problem is minimized.

For the implementation of the MPC concept, the optimization problem must be recurrently solved for overlapping, future time horizons, cf. **Fig. 7**. However, only the optimized inputs in the non-overlapping time intervals are actually applied to the furnace. The solution in the remaining time interval is discarded or used for the initialization of the optimization variables of the subsequent MPC horizon.

At the beginning of each time horizon, the current system state is required as an initial condition, i.e., it serves as feedback. Because only very few states are available by measurements, the system state is estimated by means of a state observer. Based on the furnace model, the state observer uses only the system inputs and the available measurements for an improvement of the current estimation. In addition, the observer can be used for the estimation of slowly varying material parameters.

EXAMPLE PROBLEM

To demonstrate the capabilities of AFC, a simulation study is carried out. In the simulation, the real plant is replaced by the presented furnace model [2-4]. Strip data, i.e., geometric dimensions, material properties, target temperatures, and corresponding temperature constraints, are taken from a real production process at the combined direct- and indirect-fired strip annealing furnace of voestalpine Stahl GmbH in Linz, Austria. In the considered simulation study, 21 strips are processed, where the strip thickness is in the range from 0.6-0.8 mm and the width is in the range from 1.3-1.5 m. Because the most important goal is strip temperature control, the proposed concept is verified by means of the strip temperatures at the two pyrometer positions at the end of the RTH and the RTS section, cf. Fig. 1. As can be seen from **Fig. 8**, the strip temperature accurately

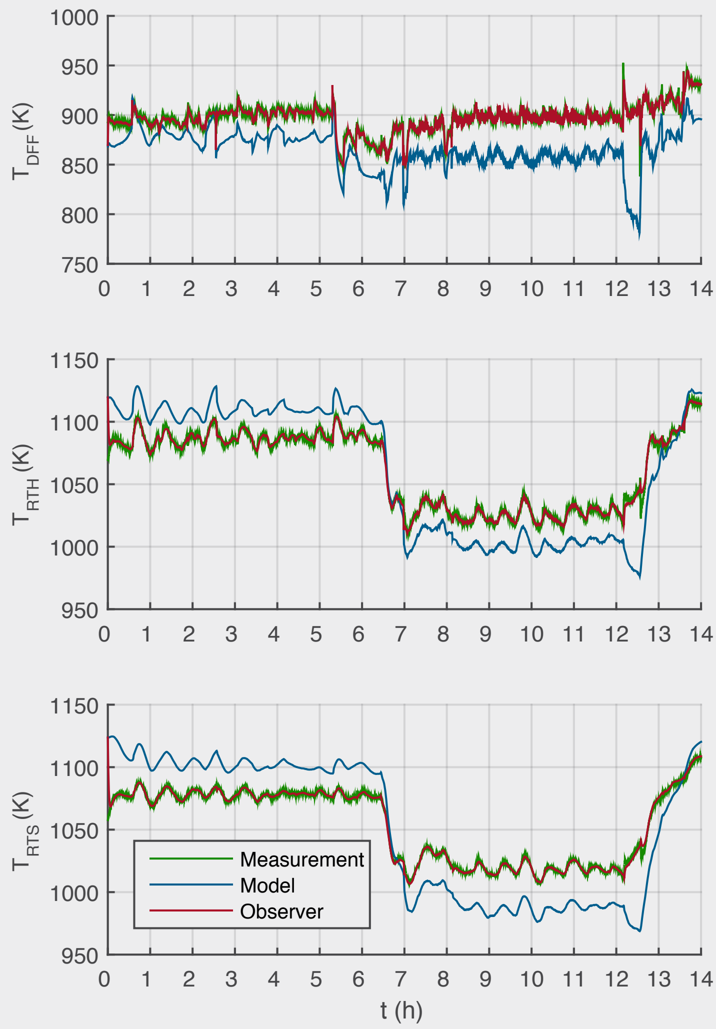

Fig. 6: Validation of the mathematical model and the observer

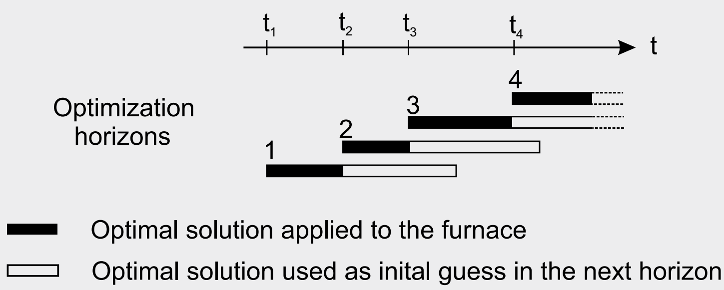

Fig. 7: Receding horizon approach

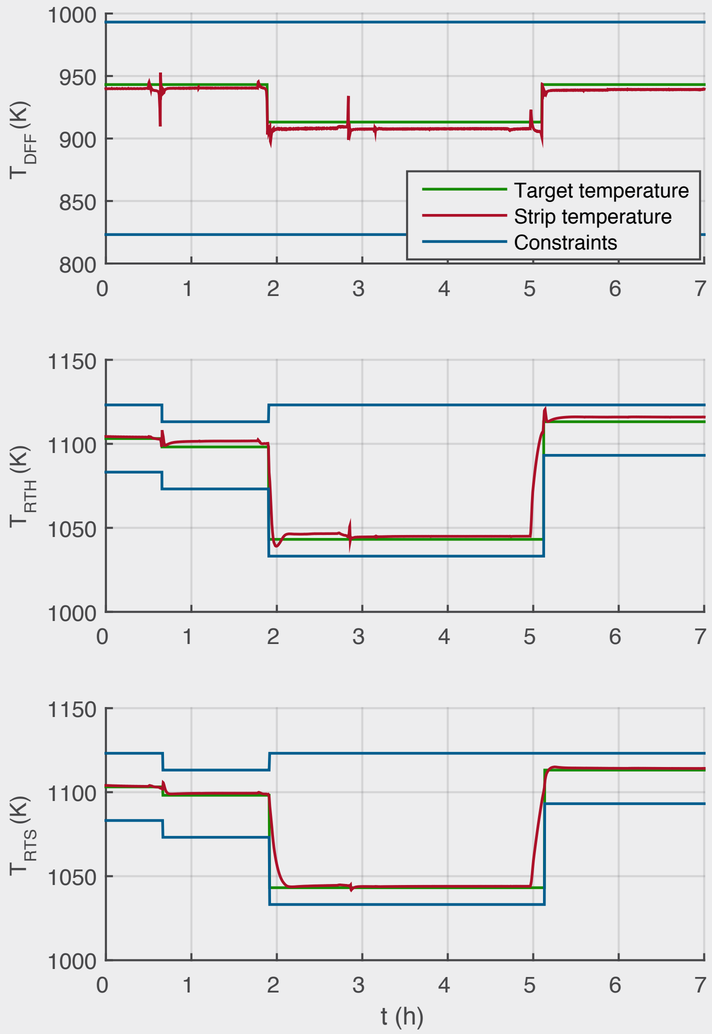

Fig. 8: Simulated strip temperatures (red) and corresponding target temperatures (green) as well as the temperature constraints (blue) at the pyrometer positions

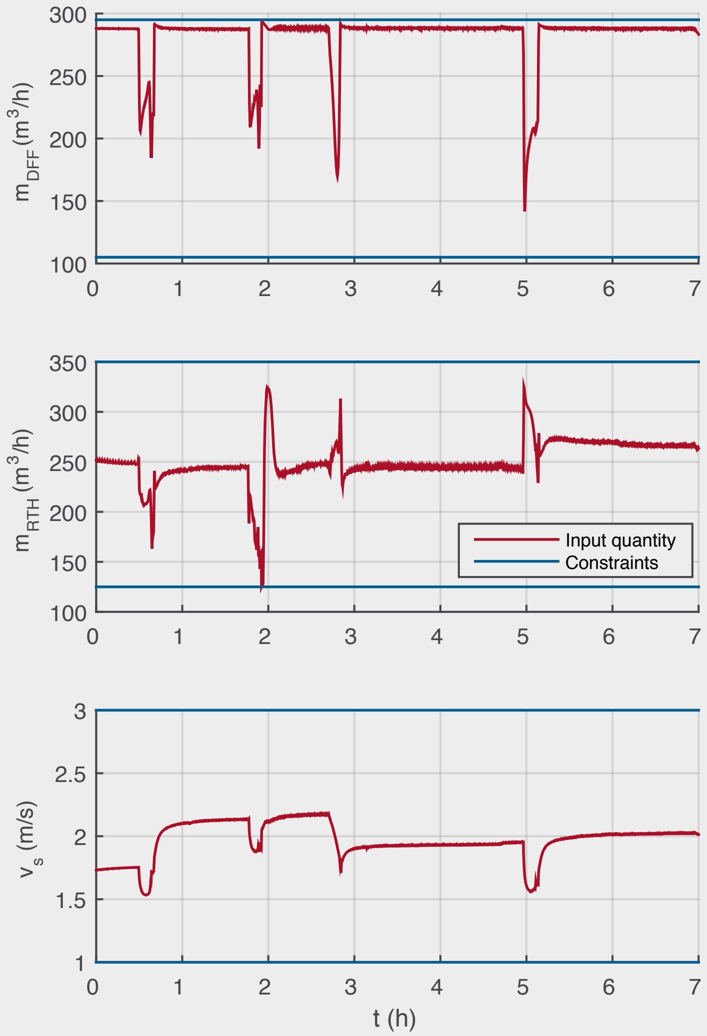

Fig. 9: Simulated system inputs, i.e., mass flow of fuel to a heating zone of the DFF and RTH and strip velocity, and corresponding constraints

follows the respective target temperature and is always within the tolerance range. This also holds true in transient operational situations, i.e., when a welded joint that connects two different strips moves through the furnace. **Fig. 9** shows examples of system inputs, i.e., the gas mass flow in a heating zone of both the direct-fired and the indirect-fired furnace section and the strip velocity. These quantities are also within their limits.

CONCLUSION

In this work, a model-based control concept called ANDRITZ Advanced Furnace Control (AFC) is presented. It can handle the rising quality demands and growing product ranges in continuous strip annealing furnaces. The primary control goal is the optimal heating of the strip. Moreover, maximum throughput and minimum energy consumption constitute secondary control goals and can also be taken into account by the AFC. The proposed concept consists of four building blocks the observer, the model predictive control, the trajectory planning, and the offline simulator. Each of these modules carries out a specified task to meet the desired goals.

The basis of AFC is a mathematical furnace model based on balances and constitutive equations. Moreover, thermal radiation was modelled by the zone and the net-radiation method. Finally, the model was verified by means of measurements from a real plant.

A model predictive control concept developed by ACIN, Vienna University of Technology, [13], which is based on the proposed model, was utilized. Here, a suitable optimization problem was defined with respect to the properties of the considered furnace. The problem was solved by the Gauss-Newton method. The required initial conditions are provided by the model-based state observer. The observer is also based on the model. The capabilities of the control concept are demonstrated by means of an example problem.

Due to its flexible design, the applicable range of AFC is not limited by age or vendor of the strip processing line, since it can be easily adapted to the project specific requirements. Additional information on the AFC system can be found in [14].

ACKNOWLEDGEMENTS

This research was partially supported by the Austrian Research Promotion Agency (FFG), grant number: 834305. Moreover, the authors kindly express their gratitude to the industrial research partner voestalpine Stahl GmbH.

LITERATURE

[1] Luo, H.; Dunbar, W. S.; Moore, J. E.: "Buckling analysis of a heat steel strip in a continuous annealing furnace," Manufacturing Science an Engineering, vol. 12, no. 4, pp. 457-464, 1999

[2] Niederer, M.; Strommer, S.; Steinboeck, A.; Kugi, A.: "A mathematical model of a combined direct- and indirect-fired strip annealing furnace," in Proceedings of the 10th International Conference on Zinc and Zinc Alloy Coated Steel (GALVATECH), Toronto, Canada, 2015

[3] Niederer, M.; Strommer, S.; Steinboeck, A.; Kugi, A.: "A simple control-oriented model of an indirect-fired strip annealing furnace," International Journal of Heat and Mass Transfer, vol. 78, pp. 557-570, 2014

[4] Strommer, S.; Niederer, M.; Steinboeck, A.; Kugi, A.: "A mathematical model of a direct-fired continuous strip annealing furnace," International Journal of Heat and Mass Transfer, vol. 69, pp. 375-389, 2014

[5] Chen, T.-C.; Ho, C.-H.; Lin, J.-C.; Wu, L.-W.: "3-D temperature and stress distributions of strip in preheating furnace of continuous annealing line," Journal of Applied Thermal Engineering, vol. 30, pp. 1047-1057, 2010

[6] Flechter, C.: Computational Galerkin methods, Berlin, Heidelberg: Springer-Verlag, 1996

[7] Modest, M.: Radiative heat transfer, San Diego: Academic Press, 2003

[8] Feischl, M.; Führer, T.; Niederer, M.; Strommer, S.; Steinboeck, A.; Praetorius, D.: "Efficient numerical computation of direct exchange areas in thermal radiation analysis," Submitted to Numerical Heat Transfer, Part B: Fundamentals, 2016

[9] Incropera, F. P.; Dewitt, D. P.; Bergmann, T. L.; Lavine, A. S.: Fundamentals of heat and mass transfer, Hoboken, New Jersey: John Wiley and Sons, 2007

[10] Kokotovic, P.; Khalil, H. K.; O'Reilly, J.: Singular perturbation methods in control, Philadelphia: Society for Industrial and Applied Mathematics (SIAM), 1999

[11] Holmes, M. H.: Introduction to numerical methods in differential equations, New York: Springer-Verlag, 2007

[12] Papageorgiou, M.: Optimierung, München: Oldenbourg Verlag, 1991

[13] „Automation and Control Institute (ACIN), Vienna University of Technology – Homepage," [Online]. Available: www.acin.tuwien.ac.at/forschung/cds

[14] "Andritz Metals – Homepage," [Online]. Available: http://www.andritz.com/index/metals.htm

AUTHORS

Dipl.-Ing. **Martin Fein**
Andritz AG
Vienna, Austria
Tel.: +43 (0) 5 0805 55147
martin.fein@andritz.com

Dipl.-Ing. **Michael Böck-Schnepps**
Andritz AG
Vienna, Austria
Tel.: +43 (0) 5 0805 55501
michael.boeck-schnepps@andritz.com

Dipl.-Ing. **Stephan Strommer**
Automation and Control Institute
Vienna University of Technology
Vienna, Austria
Tel.: +43 (0) 1 58801 376290
strommer@acin.tuwien.ac.at

Dipl.-Ing. **Martin Niederer**
Automation and Control Institute
Vienna University of Technology
Vienna, Austria
Tel.: +43 (0) 1 58801 376292
niederer@acin.tuwien.ac.at

Dr. techn. **Andreas Steinboeck**
Automation and Control Institute
Vienna University of Technology
Vienna, Austria
Tel.: +43 (0) 1 58801 376264
steinboeck@acin.tuwien.ac.at

Univ. Prof. Dr. techn. **Andreas Kugi**
Automation and Control Institute
Vienna University of Technology
Vienna, Austria
Tel.: +43 (0) 1 58801 37614
kugi@acin.tuwien.ac.at