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Nonlinear model predictive control of the strip temperature in an annealing furnace

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ABSTRACT

A nonlinear model predictive controller is designed for the strip temperature in a combined direct- and indirect-fired strip annealing furnace. Based on a tailored first-principles dynamical model and the estimated current system state, the receding horizon controller selects optimal trajectories for both the fuel supply and the strip velocity so that the strip temperature is controlled to its desired target temperature. The controller additionally maximizes the throughput and minimizes the energy consumption. In the control algorithm, the dynamic optimization problem with equality constraints is numerically solved by using the Gauss–Newton method. The gradient and the approximated Hessian matrix of the objective function are analytically computed using an adjoint-based method. The capabilities of the proposed controller are demonstrated for a validated high-fidelity simulation model of an industrial annealing furnace.

1. Introduction

1.1. Control problem

In the steel industry, strip annealing furnaces are used for the heat treatment of steel strips in order to achieve the desired metallurgical and surface properties for subsequent process steps. The annealing furnace considered in this paper, cf. Fig. 1, is part of a strip processing line of voestalpine Stahl GmbH in Linz, Austria and contains 235 m steel strip. The key parameters of the furnace are tabulated in Table 1. To ensure a continuous operation of the processing line, the strips are welded together to form an endless strip.

To meet the high demands on the quality of the final product, the temperature evolution of the strip is of importance. While the strip moves through the furnace, it has to be heated to a predefined target temperature. This strip temperature control task is a challenge mainly for the following reason: An ongoing diversification of the product portfolio essentially prevents steady-state furnace operation. The furnace can be considered as a cascade thermal system, where the strip is part of the last cascade. Since the thermal inertia of the strip is significantly lower than that of the furnace, it is difficult to consistently realize the desired target temperature in transient operational situations.

In addition to the product quality, there are further demands on the furnace operation like optimized energy consumption, material throughput, and CO_2 emissions. A furnace temperature controller that meets all these requirements is still an open research issue. This paper, therefore, explores the suitability of advanced nonlinear control and optimization methods for the considered control problem.

1.2. Existing solutions

In the literature, different concepts for strip temperature control of annealing furnaces can be found. The following summary should therefore only serve as a starting point for an in-depth exploration.

Over decades, simple PID control concepts were used for strip temperature control. PID control does not require a mathematical model and provides acceptable results for a steady-state furnace operation. However, if the furnace is not operated at steady state, this concept is no longer suitable because of the large thermal inertia of the furnace.

Occasionally, rule-based expert systems and fuzzy logic control concepts are used, see, e.g., [1–5]. Generally, these semi-empirical concepts use a wide range of measurements from the plant in order

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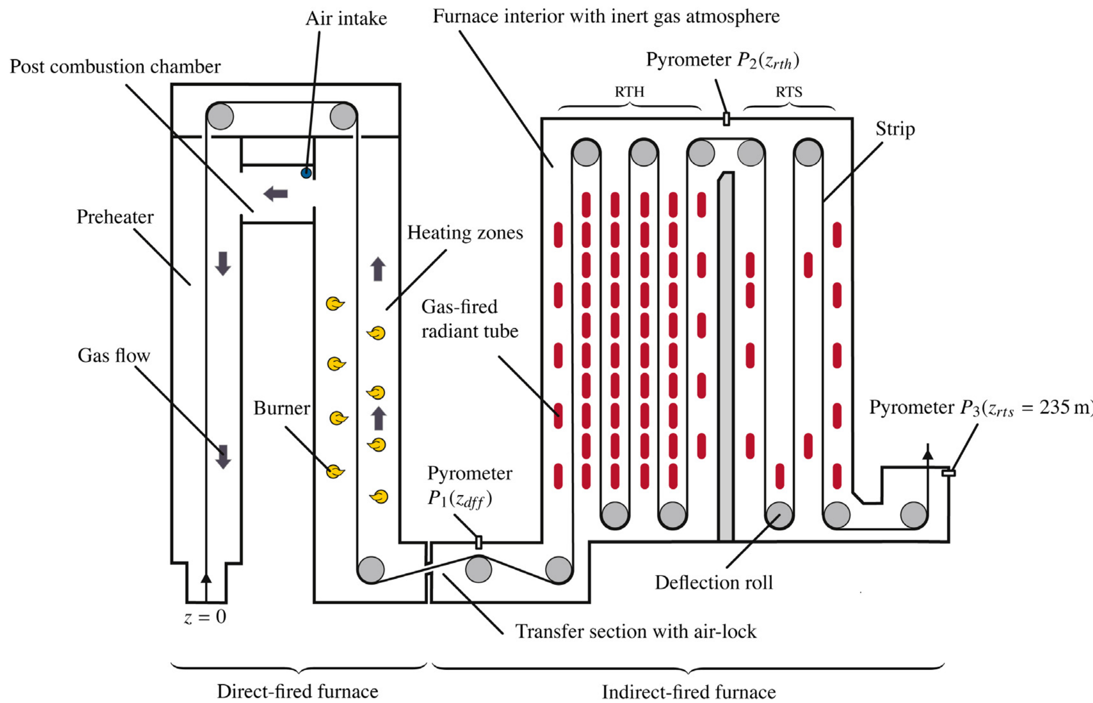

Fig. 1. Combined direct- and indirect-fired strip annealing furnace.

to characterize the operation conditions and adjust the inputs to obtain the desired temperature. Basically, they mimic the human operator but they perform the control task with greater consistency and accuracy and smaller response times than humans. Due to the complexity and wide variety of operation situations of an annealing furnace, these control concepts are, however, expensive to install, commission, and tune.

A hierarchical control concept is presented in [6]. In the top-most layer, set-point values for the line speed and the zone temperatures needed to achieve the target strip temperature are determined. In the intermediate layer, the switching times of the individual set-point values are determined using a simple model of the strip temperature and optimization based methods. In the inner-most layer, simple line speed and temperature controllers control the strip temperature and ensure that it is within defined bounds.

A hierarchically structured model-based control concept is also presented in [7]. The underlying semi-analytic furnace model is based on physical principles and measured system dynamics. In the higher control layer, reference trajectories for both the strip velocity and the strip temperature are generated. In the lower control layer, unknown parameters of the model are recursively estimated and the mass flows of fuel are determined using generalized predictive control [8,9].

A control concept without a hierarchical structure is presented in [10]. Based on a linear model of the strip temperature, a model predictive controller for the heating power of the furnace is developed. It also takes into account input constraints. The constrained optimization problem is solved by using quadratic programming [11].

The controller presented in [12] is similar to that presented in [10] but is based on a simple nonlinear furnace model. For the utilization in a linear model predictive control concept, the furnace model is linearized. In addition to the heating power of the furnace, the controller optimizes the throughput, i.e., the line speed.

Table 1
Nominal parameters of the strip annealing furnace.

Throughput of steel	45.7 t/h
Nominal heating power	15 MW
Strip dimensions	
Thickness	0.35–1.2 mm
Width	800–1640 mm
Strip velocities	Max. 180 m/min
Number of gas burners	48
Number of radiant tubes	62
Number of heating zones	7

1.3. Motivation, objectives, and contributions of this work

Nonlinear model predictive control is an appropriate concept for strip temperature control of the considered annealing furnace. It is a versatile optimization-based and anticipative control method that is suitable for complex nonlinear multiple-input multiple output systems. Moreover, it allows the incorporation of various control objectives and the systematic consideration of input constraints, state constraints, and known disturbances, e.g., strip changes.

Most developed model predictive controllers for strip temperature control of annealing furnaces are based on linear system models. Though a linear model simplifies the control law, it may limit the capability and the accuracy of the obtained controller. Moreover, existing strip temperature controllers are mainly developed for indirect-fired annealing furnaces. However, the annealing furnace considered in this paper features also a direct-fired section. Since the direct- and the indirect-fired furnace sections are physically coupled by the moving steel strip, an integrated controller design for both furnace sections is recommendable. For this reason, existing control strategies cannot be directly transferred to the annealing furnace considered here. This motivates the tailored design of a nonlinear model predictive controller for non-steady-state furnace operation. It should realize the following control objectives:

- Accurate strip temperature control.
- Maximization of the throughput of the steel strip.