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Hierarchical nonlinear optimization-based controller of a continuous strip annealing furnace

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ABSTRACT

Continuous strip annealing furnaces are complex multi-input multi-output nonlinear distributed-parameter systems. They are used in industry for heat treatment of steel strips. The product portfolio and different materials to be heat-treated is steadily increasing and the demands on high throughput, minimum energy consumption, and minimum waste have gained importance over the last years. Designing a furnace control concept that ensures accurate temperature tracking under consideration of all input and state constraints in transient operations is a challenging task, in particular in view of the large thermal inertia of the furnace compared to the strip. The control problem at hand becomes even more complicated because the burners in the different heating zones of the considered furnace can be individually switched on and off. In this paper, a real-time capable optimization-based hierarchical control concept is developed, which consists of a static optimization for the selection of an operating point for each strip, a trajectory generator for the strip velocity, a dynamic optimization routine using a long prediction horizon to plan reference trajectories for the strip temperature as well as switching times for heating zones, and a nonlinear model predictive controller with a short prediction horizon for temperature tracking. The mass flows of fuel and the strip velocity are the basic control inputs. The underlying optimization problems are transformed to unconstrained problems and solved by the Gauss–Newton method. The performance of the proposed control concept is demonstrated by an experimentally validated simulation model of a continuous strip annealing furnace at voestalpine Stahl GmbH, Linz, Austria.

1. Introduction

Continuous annealing processes are used for heat treatment of steel strips. Controllers should ensure that the strip temperature follows a set-point temperature trajectory as closely as possible. The set-point trajectories depend on metallurgical requirements and may vary from strip to strip. Typically, a diverse portfolio of products is heat-treated in continuous strip annealing furnaces (CSAF). Therefore, a variety of different CSAF can be found in industry (Mullinger & Jenkins, 2014; Imose, 1985). The CSAF considered in this paper is part of a hot-dip galvanizing line of voestalpine Stahl GmbH, Linz, Austria.

The accurate temperature control of a CSAF is essential to ensure a high product quality. This is in particular challenging in transient operational situations when a welded joint moves through the furnace. In this case, the strip dimensions (thickness, width), the steel grade, the set-point strip temperature, and the strip velocity may change. Since the strip temperature is a distributed process variable, which can only be measured at a very few discrete points, the control task is further complicated. Moreover, the thermal inertia of the furnace is rather high compared to that of the strip. Thus, the response time of the furnace is also high compared to the processing time of a strip.

The CSAF constitutes a multiple-input multiple-output nonlinear distributed-parameter system. The main control inputs are the fuel supplies of the heating zones. They can be individually switched on/off depending on the required heat input, which makes the task of finding optimal control inputs a mixed-integer programming problem (Grossmann & Kravanja, 1997). The strip velocity serves as an additional control input. It is subject to several restrictions which are mainly defined by downstream process steps. All control inputs are bounded from above and below. In this work, a nonlinear optimization-based hierarchical control strategy for the considered CSAF of voestalpine Stahl GmbH is presented.

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Nomenclature

Latin symbols

b	width
c	specific heat capacity
$\mathcal{D} = \{hza, hzb, hzc, hzd\}$	set of abbreviations for the heating zones a–d
d	thickness
$\mathbf{d}$	search direction
$\mathcal{F} = \{dff, rth, rts\}$	set of abbreviations for furnace sections
$\mathbf{g}$	gradient
$\dot{H}$	enthalpy flow
$\mathbf{H}$	Hessian
h	specific enthalpy
i	index
J	objective function
k	index with respect to time
$\mathbf{L}$	vector-valued Lagrange function
l	index
$\dot{M}$	mass flow
$\bar{M}$	molar mass
$\mathbf{m}$	vector of the mass flows of fuel
$\dot{\mathbf{m}}$	slope of the mass flows of fuel
N	number of discretized elements
$\dot{Q}$	heat flow
$\dot{q}$	heat flux
$\mathbf{R}$	objective function
S	surface
s	switching state
T	temperature
t	time
$\mathbf{U}$	system input
$\mathbf{u}$	optimization variables
v_s	strip velocity
$\dot{v}_s$	slope of the strip velocity
$\mathbf{W}$	weighting matrix
$\mathbf{x}$	algebraic and state variables
$\mathbf{y}$	system outputs
z	spatial coordinate

Greek symbols

ε	emissivity
$\boldsymbol{\Gamma}$	system dynamics
$\boldsymbol{\Lambda}$	Lagrange multiplier
λ	air–fuel equivalence ratio
φ	nonlinear transformation
ρ	mass density
τ	switching time
υ	unconstrained optimization variable
χ	stoichiometric coefficient

Subscripts

g	flue gas
h	roll
r	radiant tube
s	strip
w	wall

Superscripts

$+$	upper bound
$-$	lower bound
ad	adiabatic flame
a	air
cb	combustion
d	set point
f	fuel
in	incoming
out	outgoing
r	reference
sp	nitrogen flushing
$\hat{}$	observer

1.1. *Continuous strip annealing furnace*

Fig. 1 shows a schematic of the considered CSAF, which consists of a direct- and an indirect-fired furnace separated by an air lock. In the considered CSAF, standard steel for the automotive area (bodywork) is produced. The strip width varies from 0.8 m up to 1.8 m, whereas the strip thickness typically varies from 0.4 mm up to 1.2 mm due to the production needs but can accept materials having lower thickness. The steel strip, which is conveyed through the furnace by rolls, couples both parts. This furnace type is designed for heat treatment of steel strips in terms of throughput, energy consumption, and product quality (Imose, 1985).

In the direct-fired furnace (DFF), the strip is heated by means of hot flue gas, which comes from the combustion of fuel. The fuel is burnt fuel rich in the four heating zones (hz a–d) to avoid scale formation of the strip. Thus, the flue gas contains unburnt products, which are burnt in a post combustion chamber (PCC) by adding fresh air via an air intake. The flue gas leaving the PCC contains excess oxygen and streams into the preheater, where it is used to preheat the incoming strip. The DFF is a counterflow heat exchanger because the flue gas streams in the opposite direction of the strip motion.

In the heating zone a and b, an array of burners is used, where a defined number of burners can be deactivated depending on the width of the strip (narrow, middle, wide). These heating zones are responsible for the base load. Using shut-off valves, the fuel supply of the heating zones a–d can be individually switched on/off. Deactivated burners are flushed with cold nitrogen to protect the burner nozzles from thermal damage (Strommer, Steinboeck, Begle, Niederer, & Kugi, 2014b). The media supplies of air and fuel are coupled by the air–fuel equivalence ratio, which is controlled by a cross-limiting controller.

The indirect-fired furnace (IFF) is separated into three sections, the radiant tube heating sections 1 and 2 (rth 1 and 2) and the radiant tube soaking section (rts). Each of these sections is equipped with W-shaped radiant tubes and can be separately controlled. The tubes are permanently supplied with fuel and air to avoid flame extinction. Inside the IFF, an inert gas atmosphere is established to prevent scale formation of the strip. Due to a controlled pressure gradient, a gas flow in the direction of the DFF is always assured.

The strip temperature is measured by three pyrometers (P_{dff}, P_{rth}, and P_{rts}), see Fig. 1. Additionally, thermocouples, which measure several local flue gas temperatures, wall temperatures, and radiant tube temperatures, are installed for safety reasons.

1.2. *Existing solutions*

Control concepts that can be found in the literature significantly differ in their complexity and application. In CSAFs, simple PID controllers are widespread to control the heating of the strip. In Dunoyer, Burnham, Heeley, and Marcroft (1998) and Martineau, Burnham, Haas, Andrews, and Heeley (2004), PID controllers based on mathematical models of the furnace are applied. The PID controller proposed by Li, Liu, Jian, and Guo (2004) is used to control the temperature of a workpiece inside a furnace. The parameters of this controller were determined by an optimization problem. In Kelly, Watanapongse, and Gaskey (1988), a