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A mathematical model of a direct-fired continuous strip annealing furnace

S. Strommer*, M. Niederer, A. Steinboeck, A. Kugi

Automation and Control Institute, Vienna University of Technology, Gusshausstrasse 27–29, 1040 Wien, Austria

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ABSTRACT

A mathematical model of a direct-fired continuous strip annealing furnace is developed. The first-principle model uses the heat balance to describe the dynamic behavior of the strip and the rolls. The mass and the enthalpy balance are employed to calculate the mass, the composition, and the temperature of the flue gas. The heat conduction equation of the furnace wall is discretized by means of the Galerkin method. Furthermore, the convective and radiative heat transfer interconnect all submodels of the furnace. For the calculation of the radiative heat transfer, the zone method is utilized. Finally, the assembled model is reduced by applying the singular perturbation method. A comparison of simulation results with measurement data from a real plant demonstrates the accuracy of the reduced model. Moreover, due to the moderate computational effort, the model is suitable for real-time applications in control and dynamic optimization.

1. Introduction

1.1. Objective

In continuous annealing furnaces, see, e.g., [25,26], metal strip products are heat-treated. The direct-fired strip annealing furnace considered in this paper is part of a hot-dip galvanizing line at voestalpine Stahl GmbH, Linz, Austria. A schematic diagram of this furnace is depicted in Fig. 1. The galvanizing line also contains an indirect-fired furnace (IFF) [25], which comes right after the direct-fired furnace but will not be detailed in this paper. Based on metallurgical requirements the strip has to be heated from ambient temperature along a predefined heating curve to a desired target temperature at the outlet of the furnace.

Temperature control of strip annealing furnaces is a challenging task, in particular in transient operating situations when there are changes in the strip dimensions (width, thickness), the velocity or the steel grade. A further difficulty for temperature control is that the strip temperature can only be measured at a very few discrete points mostly by means of pyrometers. Moreover, due to their high energy consumption, continuous strip annealing furnaces are important cost drivers of strip processing lines. This is why, apart from the product quality, minimum energy consumption, minimum flue gas emissions and minimum operating costs constitute further major control objectives. These objectives demand the application of advanced (nonlinear) control and optimization methods [2,3,23], which systematically take into account the essential nonlinearities, the dynamical interactions and the delays of the overall system. For this, tailored mathematical models have to be developed, which constitute a reasonable compromise between accuracy and complexity and serve as a basis for real-time control and optimization.

1.2. Direct-fired furnace

The furnace considered in this analysis (cf. Fig. 1) contains approximately 50 m strip, which moves at velocities in the range of 1.5 – 3 m/s through the furnace. The maximum strip thickness is 1.2 mm and the width can be up to 1.7 m. The insulating materials of the furnace walls are refractory and the guiding rolls are made of high temperature alloy.

In essence, the hot flue gas streams in the opposite direction of the strip through the furnace and, therefore, the furnace may be considered as a counter-flow heat exchanger. At the air lock 1 (right side of Fig. 1), which represents the interface between the direct- and the indirect-fired furnace, inert gas from the indirect-fired furnace enters the direct-fired furnace. The inert gas atmosphere in the indirect-fired furnace is used to avoid scale formation. Between the air lock 1 and the air lock 2, there are four heating zones (HZ A – D), each equipped with a set of burners supplied by natural gas. For quality reasons, the strip must not be oxidized, which is why a substoichiometric combustion has to be ensured. Thus, the flue gas that leaves the heating zone HZ D

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* Corresponding author. Tel.: +43 158801 376290; fax: +43 158801 37699.
E-mail address: strommer@acin.tuwien.ac.at (S. Strommer).

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Nomenclature

Latin symbols

Bi	Biot number
c_p	specific heat capacity
d	thickness
d_r	diameter of the roll
H	enthalpy of the flue gas
$\dot{H}$	enthalpy flow of the flue gas
h	absolute (specific) enthalpy
h_c	convection heat transfer coefficient
$\tilde{h}_l$	latent heat
J	cost function
K	attenuation coefficient
k	thermal conductivity
M	mass
$\dot{M}$	mass flow
$\overline{M}$	molar mass
$\mathbf{M}_q$	local heat flux mapping matrix
$\mathbf{M}_T$	temperature mapping matrix
N	number of volume zones
Nu	Nusselt number
N_s	number of surface sections
$\overline{N}_s, \tilde{N}_s$	number of finite sections in Eulerian and Lagrangian coordinates
N_g	number of subvolumes
Pr	Prandtl number
$\mathbf{P}$	radiation mapping matrix
p	pressure
$\dot{Q}$	heat flow
$\dot{\mathbf{Q}}$	vector of heat flows
$\dot{q}, \dot{\tilde{q}}$	heat flux in Eulerian and Lagrangian coordinates
$\dot{\mathbf{q}}$	vector of heat fluxes
Re	Reynolds number
R_{con}	thermal contact resistance
R	specific gas constant
S	surface area
$\mathbf{S}$	vector of surface areas
T	temperature
$\tilde{T}$	temperature in Lagrangian coordinates
$\mathbf{T}$	vector of temperatures
t_e, t_b	start and end time
$\mathbf{u}$	input vector
V	volume
v	trial function
v_s	strip and roll velocity
x, y, z	Eulerian coordinates
$\tilde{x}, \tilde{y}, \tilde{z}$	Lagrangian coordinates
$\mathbf{x}$	state vector
$\mathbf{z}_1, \mathbf{z}_2$	state vectors of the fast and slow subsystem
$\breve{\mathbf{z}}_1, \breve{\mathbf{z}}_2$	state vectors of the quasi-steady-state system

Greek symbols

α	flow coefficient
χ	number of moles
$\Delta\tilde{h}_s$	sensible heat
ε	emissivity coefficient
λ	excess air coefficient
μ	dynamic viscosity
ρ	mass density
Δt_k	sampling time
ξ	mass fraction
$\Delta z, \Delta\tilde{z}$	length of a finite section in Eulerian and Lagrangian coordinates

Subscripts

g	flue gas
r	roll
s	strip
v	volume
w	wall

Superscripts

a	air
cb	combustion
f	fuel
in	incoming
out	outgoing

contains unburnt gas, which is oxidized in a post combustion chamber (PCC) by adding fresh air (cf. air intake in Fig. 1).

The section between the air lock 2 and the contraction is referred to as transition zone top. A small amount of the flue gas flows through the air lock 2, which can be considered as an orifice connecting the heating zones and the transition zone top. However, most of the flue gas leaves the HZ D through a bypass which includes the PCC. After burning the remaining combustible components in the PCC, the flue gas does not contain any oxidizable or potentially harmful elements and may be released into the environment or further used, e.g., for preheating the combustion air or the strip (cf. Fig. 1).

The flap valve 2, which works like an orifice, controls the gas flow from the PCC to the so-called bypass. This duct allows to bypass flue gas (typically a small amount) directly into the funnel. However, the majority of the burnt flue gas flows into the furnace section between the contraction and the air lock 3, which is called preheater (PH). There, the remaining sensible heat of the flue gas is used for preheating the strip. The air lock 3 can also be considered as an orifice, where depending on the pressure conditions flue gas leaves the furnace or fresh air flows into the PH. Generally, the mass flow of gas through the air lock 3 is rather small. The flue gas from the PH leaves the furnace through the funnel. A suction fan (not shown in Fig. 1) controls the suction pressure to a value less than the atmospheric pressure, which makes the flue gas to stream to the funnel. Moreover, a recuperator (not shown in Fig. 1) utilizes the remaining enthalpy of the hot flue gas to preheat the combustion air for the burners in the HZ C and HZ D.

1.3. Existing models

A large number of different approaches for modeling a strip annealing furnace can be found in the literature.

One way of setting up such a furnace model is the use of computational fluid dynamics (CFD), which allows high-resolution evaluations of the heat and mass flows in the furnace [4,9,10]. CFD models typically take into account the combustion process, the furnace geometry, and the energy exchange between the strip, the flue gas, the furnace walls, and the rolls. Due to their complexity and high dimensions, CFD models are usually not directly suitable for control design and real-time applications. The use of CFD is more common in the design of new furnaces and in off-line studies.

For model-based control applications, physical or empirical models are required that are computationally inexpensive. The models