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A new approach for estimation of total heat exchange factor in reheating furnace by solving an inverse heat conduction problem

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ABSTRACT

The estimation of the total heat exchange factor plays an important role while obtaining the reference trajectories on steady-state furnace operation for the reheating furnace control system. For this purpose, this paper presents a new optimization method to estimate the total heat exchange factor by solving the inverse heat conduction problem (IHCP) in the reheating furnace. The proposed method is based on the Conjugate Gradient Method (CGM), the Levenberg-Marquardt Algorithm (LMA) and Gradient Projection method (GPM). In the proposed method, CGM is introduced for its fast convergence speed and the high accuracy, LMA is employed to assure the convergence of iteration sequence, and GPM is guaranteed to identify the active set at a solution in a finite number of iterations. The experiment results using the real plant data measured by thermocouples and the comparison between the proposed method and CGM are discussed. The results show the effectiveness on overcoming oscillation manner by the proposed approaches.

1. Introduction

In the steel industry, iron must undergo several thermal, mechanical, or thermomechanical process, which can be categorized into four steps: iron making, steel making, continuous casting and hot rolling, before it is suitable for industrial applications [1]. In the process chain, continuous reheating furnaces are often used for reheating or heat treatment of steel products before and after the rolling mill, as illustrated in Fig. 1.

The slab temperature depends significantly on the feed rate of the slabs, which is generally governed by up or downstream process steps. The range of products (dimensions, steel grade, target temperature, reheating time) is continuously increasing and changes of product types are frequent. In some cases, the furnace may even contain one-off products. Therefore, the heating process is characterized by non-steady-state operation and the slab reheating furnace is essentially a multi-input multi-output (MIMO) distributed parameter system with nonlinear physical interactions like thermal radiation.

Due to the large time constants, pure feedback control may fail to meet the stringent accuracy requirements in terms of slab temperatures. Therefore, a feed-forward or predictive control approach seems best suited for this task. In the current paper, a hierarchical control system based on the reference trajectories obtained under steady-state furnace operation, is used here for the dynamic optimization of controlling a walking-beam slab reheating furnace. As we can see from Fig. 2, the control concept is split into three levels: supervisory plant control, high-level furnace control and low-level furnace zone temperature control. Clearly, the reference trajectories obtained under steady-state furnace operation is the key of our control system. Firstly, the supervisory plant control can use these information to define the sequence of slabs, their reheating times, their target temperatures, and metallurgical constraints on their temperatures. Secondly, the main idea of high-level furnace control is to make the slabs reach predefined optimal temperature set-point values from reference trajectories obtained by the trajectory planner.

When designing the trajectory planner to obtain optimal reference temperature trajectories for each kind of slab, it is necessary to obtain an accurate steady state heat transfer model to identify the heat transfer parameters. To finish this job, what we need is the availability and accuracy of measurement data and powerful algorithm for solving Inverse Heat Conduction Problem (IHCP).

1.1. Temperature measurement in slab reheating furnaces

For slab reheating furnaces, measurement data are usually sparse and their accuracy is questionable [1]. Then the temperature measurement issues will be addressed in the following.

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Nomenclature

c	heat capacity, J/(kg K)
$h(y)$	orthogonal trial function
l	length of the steel slab along the direction y, m
J	sensitivity coefficient
M	total number of measured temperatures
N	number of upper or bottom inverted parameters
t	heating time, s
T	temperature, K
P	inverted parameter
S	objective function
$u(t)$	furnace temperatures, K
$x(t)$	Galerkin coefficients
y	y-coordinate, m

Greek

α	relaxation factor of the Armijo rule
β	step size
γ	conjugate coefficient
ε_1	small positive number
λ	thermal conductivity coefficient, W/(m K)
ρ	density, (kg/m^3)
σ	Stefan-Boltzmann constant, $W\left(m^2 K^4\right)$
δ	random number

Subscripts

0	initial time
b	bottom
c	calculation
i	the ith component of a vector
j	the jth component of a vector
k	the kth component of a vector
m	measurement

Superscript

k	the kth iteration number

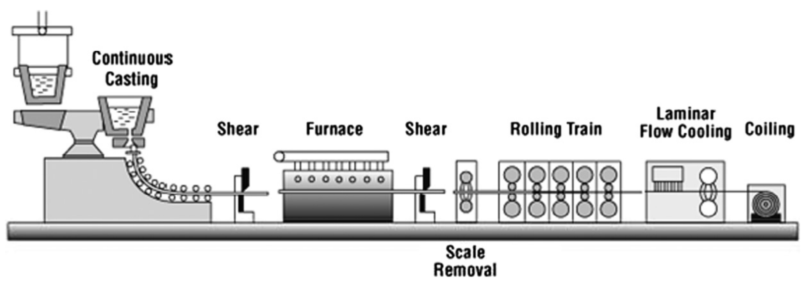

Fig. 1. The main process of the hot rolling line.

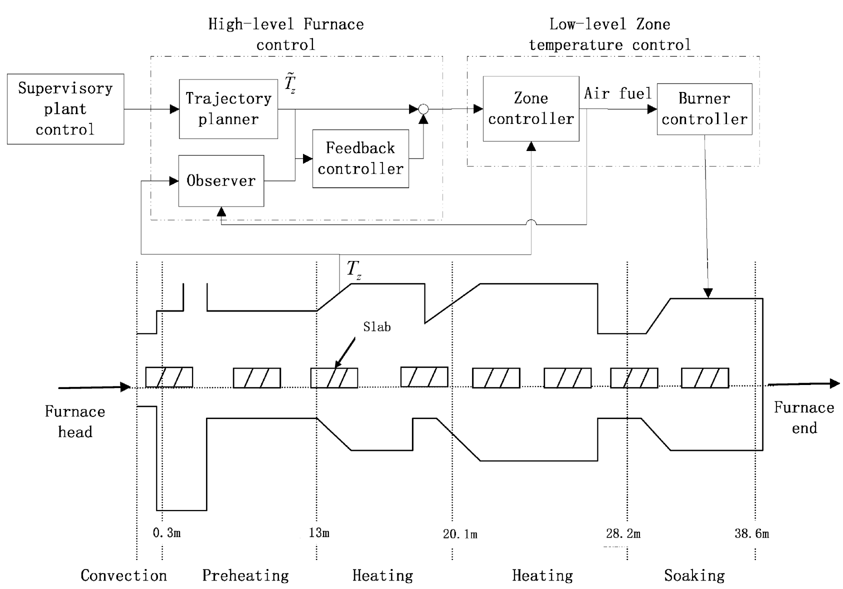

Fig. 2. The structure and hierarchical control system of the WB reheating furnace.

Thermocouples, radiation pyrometry and acoustic pyrometry are three possible methods mainly used in the reheating furnace control systems.

Thermocouples belong to the most common methods of temperature measurements inside slab reheating furnaces (for instance [2–4] and so on). Their advantages are acceptable installation and operation costs, high reliability, robustness against harsh ambient conditions, and usually satisfactory precision. Compared to pyrometers, thermocouples exhibit a slower response characteristic, which depends significantly on the installation conditions as