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Research Paper

Optimal set values of zone modeling in the simulation of a walking beam type reheating furnace on the steady-state operating regime

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HIGHLIGHTS

- The adjoint equation is introduced to the PDE optimal control problem.
- Lipschitz continuity for the gradient of the cost functional is derived.
- The simulation time and iterations reduce by a large margin in the simulations.
- The model validation and comparison are made to verify the proposed math model.

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ABSTRACT

In this paper, this study proposed a new method to solve the PDE optimal control problem by introducing the adjoint problem to the optimization model, which was used to get the reference values for the optimal furnace zone temperatures and the optimal temperature distribution of steel slabs in the reheating furnace on the steady-state operating regime. It was proved that the gradient of the cost functional could be written via the weak solution of this adjoint problem and then Lipschitz continuity of the gradient was derived. Model validation and comparison between the mathematics model and the experiment results indicated that the present heat transfer model worked well for the prediction of thermal behavior about a slab in the reheating furnace. Iterations and simulation time had shown a significant decline in the simulations of 20MnSi slab, and it was shown by numerical simulations for 0.4 m thick slabs that the proposed method was better applied in the medium and heavy plate plant, leading to better performance in terms of productivity, energy efficiency and other features of reheating furnaces.

1. Introduction

In the steel industry, the walking-beam reheating furnace (WB), which serves as a heating and buffer zone, is positioned between the continuous casting and the rolling apparatus, as illustrated in Fig. 1. Its main function is used to reheat the material, which is to raise the temperature of slab up to the target temperature while maintaining a uniform temperature in the slab with a temperature gradient not greater than the exit of furnace [1]. Before entering the rolling section, the slabs should be reheated to a temperature of approximately 1100–1500 °C, otherwise a product with unacceptable metallurgical properties could result [2]. The geometry of the WB reheating furnace is simplified, as outlined in Fig. 2. As indicated in Fig. 2, the WB reheating furnace is separated into 5 zones, and the slabs are arranged in one or several parallel rows. The furnace is 40.1 m long, 12.5 m wide, and between 4.1 m and 7.4 m high. The thicknesses of slabs is ranging from 0.15 m to 0.4 m.

Temperature control of slab furnaces is of crucial importance to safety, product quality, the achievable throughput rate, and the energy consumption [3]. However, temperature control will be a challenging task, as the slab temperatures, i.e., the most relevant process variables cannot be measured. Due to the large time constants, simple feedback control may fail to meet the stringent accuracy requirements in terms of slab temperatures. Therefore, a hierarchical control system seems best suited for this task.

As indicated in Fig. 2, the control task is split into supervisory plant control, high-level furnace control and low-level furnace zone temperature control.

At the topmost level, the task of supervisory plant control is to coordinate all rolling mill components, such as the reheating procedure. The supervisory controller defines the sequence of slabs, their reheating times, their target temperatures, and metallurgical constraints on their temperatures.

In the second control layer, the main purpose of the furnace control is to provide low-level controllers with optimal reference signals based on given process data (provided by the supervisory plant controller). This furnace control is composed of the trajectory planner, the state observer and the feedback controller. The

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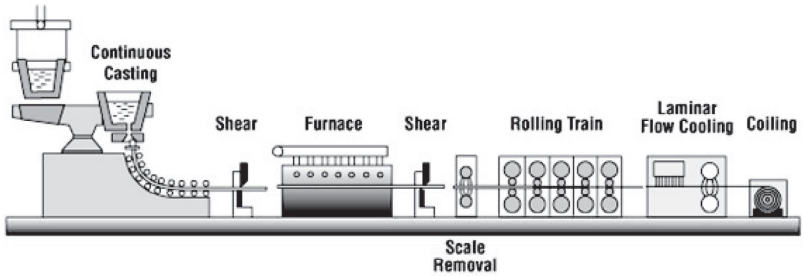

Fig. 1. The main process of the hot rolling line.

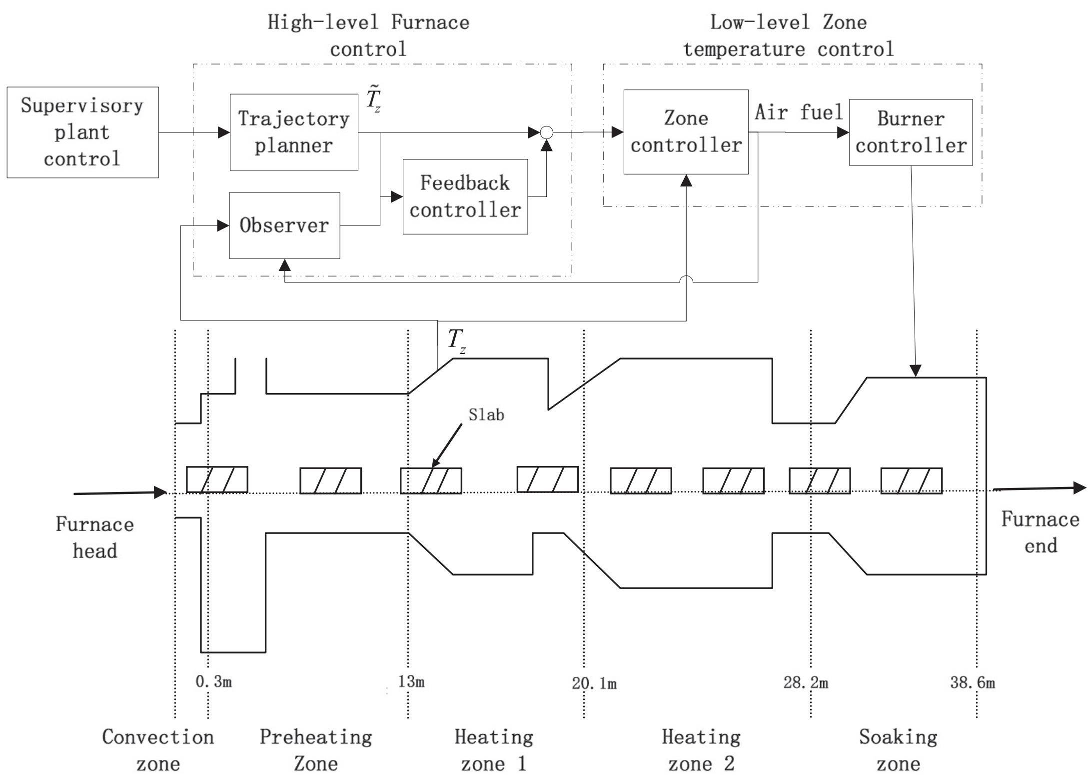

Fig. 2. The structure and hierarchical control system of the WB.

trajectory planner selects reference values for the optimal furnace zone temperatures and the optimal temperature distribution in steel slabs so that the slabs are reheated as desired. This part is the centerpiece of this paper. It will be described in the following sections. The idea of zone-based feedback controller is that the slabs should reach predefined optimal temperature set-point values (obtained by the trajectory planner). The feedback law is based on the control error of the slab temperature, which has to be estimated by the state observer. This layer requires to solve optimization problems in the closed loop in real time. The control performance can be limited because of both the temperature drop and the time delay. These effects may cause oscillations in the close loop [4,5].

In the third layer, it defines the fuel and air supplies by means of PI controller, which is carried out in the furnace by using the local furnace zone temperatures. The local furnace zone temperatures are measured by thermocouple and serv as the feedback. The burner controller regulates the fuel and air supplies to the burners by decentralized single-input single-output (SISO) controllers.

Numerous practical numerical models and methods for reheating furnace have been developed and successfully applied to various furnace geometries. The numerical studies can be usually classified into two categories. The first one solves the full Navier–Stokes and energy conservation equations governing the hot gas flow and combustion process with thermal radiative transport phenomena in a furnace [6–11]. Although the above-mentioned CFD simulations can be employed, in practice they are also too expensive because of the large computational time required. The other one analyzes the radiative heat transfer in the furnace and transient heat conduction within the slab [12–16]. This is simple but can reasonably simulate the reheating process. Although reactive flows are not involved in this method, the results are accurate enough for the temperature control of slab furnaces. This paper's control task is to get the optimization reference set-point values for the following feedback controller quickly and reliably. Thus, the second approach is employed to study the thermal behavior of the steel slabs in the present investigation.

To the author's knowledge, there has been little study on the optimization of slab heating using the adjoint equation of the PDE, which is mostly used to solve the inverse parabolic problem [17–20]. Some numerical methods such as the finite difference method (FDM) [21] and the Galerkin method (GM) [22] are applied to solve the heat transfer model. In the literature [23], the adjoint system is