Journal of University of Science and Technology Beijing
Volume 10, Number 4, August 2003, Page 69

Advanced control of walking-beam reheating furnace

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(Received 2002-06-16)

Abstract: Reheating furnace is an important device with complex dynamic characteristics in steel plants. The temperature tracing control of reheating furnace has great importance both to the quality of slabs and energy saving. A model-based control strategy, multivariable constrained control (MCC) for the reheating furnace control is used. With this control method, the furnace is treated as a six-input-six-output general model with loops coupled in nature. Compared with the traditional control, the proposed control strategy gets better temperature tracing accuracy and exhibits some energy saving feature. The simulation results show that the performance of the furnace is greatly improved.

Key words: reheating furnace; model predictive control; dynamic model; multivariable

[*This work was supported by a grant from State 863 High Technology R&D Project of China (No. 2001 AA413130) and National Natural Science Foundation of China (No.60004001).*]

1 Introduction

Walking-beam reheating furnace is an important device with lots of energy consumption in steel plants. It is important to improve the heating quality of slab and reduce the energy consumption as much as possible. In current system, the emphasis is often put on the heating quality while the energy saving is seldom taken into account. Because of high nonlinearity, large time delay, large time-constant and various uncertain factors, the modeling and reliable control of a reheating furnace are always challenging problems [1]. During the past decade, the challenge has attracted considerable attention and a significant progress has been made in the furnace control [2-6].

To obtain the requirement of temperature tracing accuracy and develop energy saving technique in the reheating furnace system, advanced control strategies are needed. In this paper, a model-based predictive control method, multivariable constrained control (MCC), was used. It treated the furnace as a multi-input-multi-output system and used the predefined temperature trajectories as a priori. The simulation results show that the strategy is very satisfactory.

2 Reheating furnace control system

2.1 Description of the reheating furnace

Walking-beam reheating furnace is a device to heat slabs. In the furnace, all slabs are heated to reach a predefined discharging temperature and a homogenization of temperature distribution in slabs is established. The distribution and move of the slab in the furnace is subjected to the heating capacity of the reheating furnace and the state of rolling line such as rolling pacing, *etc*.

The structure of the walking beam reheating furnace discussed in following sections is shown in **figure 1**. Slabs in the furnace moves from the tail zone to the soaking zone. The control area of the furnace is divided into six zones, which are denoted as zone 1 to zone 6, respectively.

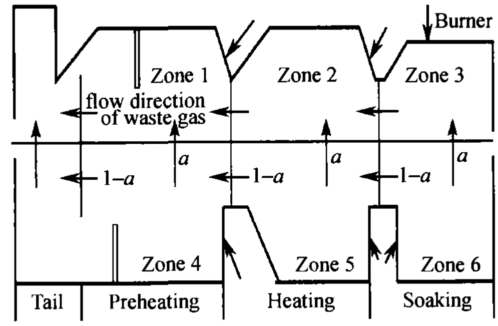

Figure 1 Structure of a walking beam reheating furnace

The function of the soaking zone is to adjust the temperature gradient so that the inner temperature and

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surface temperature of the slabs can reach a balance. The tail zone is not a control area and has no fuel input.

To control this system, an accurate dynamic model to describe the behavior of the furnace is required. Since the furnace is a multi-input-multi-output system characterized by high nonlinearity, strongly coupled, time delay, large time-constant and time variation in system parameter set and structure, it is often difficult to get an accurate model. From another point of view, the furnace is a distributed parameter system in which the distribution of temperature in the furnace is not uniform. In addition, the system suffers from uncertain disturbances.

2.2 Description of the control problem

Traditional control objective of the reheating furnace is accurate temperature tracing. With the development of computer control, some energy-saving strategies are proposed. Now the control problem includes two aspects. First, the temperature of the air in the furnace is required to trace a predefined trajectory quickly and accurately; second, advanced control of the fuel flux is taken into account, for instance, smoothing the fuel flux fluctuation. It is obvious that the traditional control method, such as PID, cannot achieve the requirement. Advanced control strategy is needed.

In basis control level, a distributed control system (DCS) is used for basic control loops, which includes air/fuel flux control and temperature control. Advanced controller is designed for giving optimized set-point value to the DCS system. In this paper, an advanced control strategy derived from model predictive control, namely MCC, is proposed. The DCS control loops and dynamic model of the furnace are regarded as a generalized object, which is a six-input-six-output system. The manipulated variable of the system is fuel flux and the controlled variable is temperature.

Since the temperatures of the six zones are strongly coupled, traditional control always needs decoupling technique. The MCC controller uses multivariable control method, so the decoupling is settled naturally. For the control of the furnace temperature, the tracing trajectories are known as a prior knowledge. The information is useful for moving horizon optimization, which is the core algorithm of the MCC controller.

2.3 Control oriented modeling of the reheating furnace

A complete model of a walking-beam reheating furnace is constructed as **figure 2**. The model consists of 4 parts, an automatic combustion control model (ACC), an advanced controller, a field control loops (DCS) model and a dynamic model of combustion process. To the advanced controller, a combination of the DCS model and the dynamic model is regarded as a generalized model.

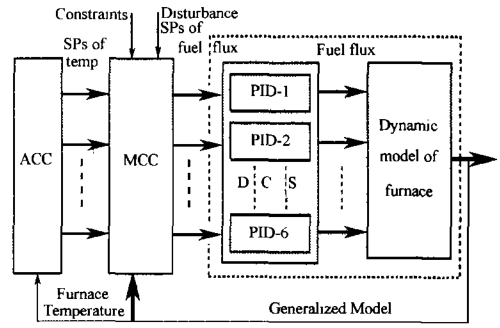

Figure 2 Control model of the reheating furnace.

(1) Automatic combustion control model.

The ACC model calculates set-points of the furnace temperatures such that the slabs in the furnace can be heated to discharging temperature. The main control method of ACC includes: calculating the average and distribution of slab temperature; determining the optimal temperature trajectory of slabs (a heating curve that describes the temperature rising of slab from which the heating quality can be guaranteed and energy can be saved) according to the furnace temperature, discharging temperature and predictive heating time in each zone; calculating the needed furnace temperature (the temperature that can guarantee the heating quality) of a certain slab; and, at last, determining the set-points of furnace temperatures of each zone through weighted average method.

(2) Advanced controller.

The advanced controller calculates the fuel flux from the derivation of furnace temperature and set-points to DCS with optimization method. The controller design will be discussed in detail at the next section.

(3) DCS model.

Control loops model, or distributed control system model (DCS) control the fuel flux of each zone according to set-points. It is the basic control loops in the production field, which directly control the valve of the fuel. Control loops in the DCS have smaller time constant compared with the dynamic model of the reheating furnace. Therefore, to the general model we use, the DCS section only has slightly influences on the entire dynamic characteristics. The main DCS control loops include the furnace temperature control loops, the gas flux and air flux control loops of the corresponding six zones. In the current system, the loop controllers are conventional PID controllers.

(4) Dynamic furnace model.

The dynamic furnace model describes the behavior of furnace at the state of rolling line and fuel flux provided by the control loop model. The objective of the dynamic modeling is to predict the furnace temperature of each zone under the fuel flux provided by DCS model and the state of slabs in the furnace. Generally, the heat exchange among slabs, furnace wall and furnace air can be formulated in a series of equations and the uncertain factors can be considered as disturbances of the system. The dynamic model is based on energy balance in which the furnace air temperature, slab temperature and furnace wall temperature should be calculated. Since the three temperatures are strongly coupled, they should be calculated simultaneously.

(a) Slab temperature tracking.

Suppose that the furnace temperature and slab temperature are linear distribution along the length direction of furnace and the thickness direction of slab respectively, the heat conduction equation of slabs in the furnace can be written as follows:

$$\begin{cases} \dfrac{\partial \theta_s}{\partial t} = a^2 \dfrac{\partial^2 \theta_s}{\partial x^2} \\ \theta_s(x,0) = \theta_{s0}(x),\ \left.\dfrac{\partial \theta_s}{\partial x}\right|_{x=\delta} = \dfrac{\phi_s}{\lambda_s},\ \left.\dfrac{\partial \theta_s}{\partial x}\right|_{x=-\delta} = -\dfrac{\phi_I}{\lambda_s} \end{cases} \tag{1}$$

where $\delta = H/2$, to a slab, H is the slab thickness, λ_s the thermal conductivity, a the heat diffusion coefficient, θ_{s0} the initial temperature, ϕ_s and ϕ_I are the top and bottom surface net radiative heat flux, respectively.

(b) Furnace wall temperature calculation.

Same as the calculation of slab temperature, the heat conduction equation of furnace wall can be written as:

$$\begin{cases} c \cdot \gamma \cdot \dfrac{\partial \theta_w}{\partial t} = \lambda_w \cdot \dfrac{\partial^2 \theta_w}{\partial x^2} \\ \left.\dfrac{\partial \theta_w}{\partial t}\right|_{t=0} = \theta_{w0}, \left.\dfrac{\partial \theta_w}{\partial x}\right|_{x=\frac{H}{2}} = q_{in}/\lambda_w, \left.\dfrac{\partial \theta_w}{\partial x}\right|_{x=-\frac{H}{2}} = -q_{out}/\lambda_w \end{cases} \tag{2}$$

where q_{in} and q_{out} are the furnace wall inner and outer surface net radiative heat flux respectively, λ_w the thermal conductivity of wall, θ_{w0} the initial temperature of wall.

(c) Heat balance in the furnace.

In the following discussion, several assumptions need to be proposed first. (I) The combustion gas and air temperatures are uniform for a zone; (II) the heat exchange is mainly maintained by radiation; (III) the air to gas ratio remains a constant; (iv) the volume of air and gas remains the same after combustion. Based on the heat exchange balance in the furnace and the assumptions above, the dynamic model can be expressed in the following form.

$$\begin{aligned} C_{pg} \cdot V_j \cdot \frac{dT_{g,j}}{dt} &= F_{f,j} H_f + A_{f,j} \cdot C_{pa} \cdot \theta_a + \\ & W_{f,j} \cdot C_{pf} \cdot \theta_f + C_{pg} \cdot \gamma_g \cdot G_{j+1} \cdot \theta_{g,j+1} - \\ & C_{pg} \cdot \gamma_g \cdot G_{j-1} \cdot \theta_{g,j-1} - \mathrm{RIFW}_j \cdot \varepsilon \cdot \sigma \cdot (T_{g,j}^4 - \theta_w^4) - \\ & \sum_{k=1}^{N_j} \mathrm{RIFS}_{j,k} \cdot \varepsilon \cdot \sigma \cdot (T_{g,i}^4 - \theta_k^4) - Q_{loss,j} \end{aligned} \tag{3}$$

where $C_{pg} \cdot V_j \cdot \frac{dT_{g,j}}{dt}$ is the energy that causes the raise of the furnace temperature; $F_{f,j}H_f$ the heat produced by the combustion of gas, $A_{f,j} \cdot C_{pa} \cdot \theta_a$ the heat energy brought in by the air, $W_{f,j} \cdot C_{pf} \cdot \theta_f$ the heat brought in by the gas, $C_{pg} \cdot \gamma_g \cdot G_{j+1} \cdot \theta_{g,j+1}$ the heat brought in from (j+1)th zone by waste gas, $C_{pg} \cdot \gamma_g \cdot G_{j-1} \cdot \theta_{g,j-1}$ the heat energy taken to (j–1)th zone by waste gas, $\mathrm{RIFW}_j \cdot \varepsilon \cdot \sigma \cdot (T_{g,i}^4 - \theta_w^4)$ the heat energy absorbed by furnace wall, $\sum_{k=1}^{N_j} \mathrm{RIFS}_{j,k} \cdot \varepsilon \cdot \sigma \cdot (T_{g,i}^4 - \theta_k^4)$ the heat energy absorbed by slabs, $Q_{loss,j}$ the heat loss in the furnace.

3 Advanced control of the reheating furnace

Multivariable advanced process control (APC) techniques have been gradually accepted in process industries, which pursue high product quality and lower cost, and have increased environmental responsibility. APC is usually model based and regulates the processes with optimization algorithms. In APC, it can usually improve the control of a process significantly by minimizing the variation in the controlled process variables, dealing with interaction among process variables and automatically controlling set-points of PID loops, which would be normally regulated by operators. In this paper, a new APC-multivariable constraint control (MCC) is proposed for the advanced control of the reheating furnace. Its kernel algorithm is derived from model predictive control (MPC), which has been greatly developed in recent 20 years, and has almost become the accepted standard for constrained multivariable control problems in the process industries. Here at each sampling time, starting at the current state, an open-loop optimal control problem is solved over a finite horizon. At the next time step the computation is repeated starting from the new state and over a shifted horizon, leading to a moving horizon policy. The core algorithm structure of MCC is shown in **figure 3**.

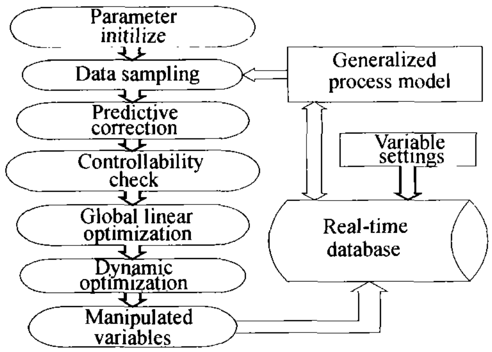

Figure 3 The core algorithm structure of MCC.

The following list briefly illustrates how it works:

(1) MCC initializes its parameters by reading recorded data from industry site and reads the outputs of the generalized model through the real time database which is mostly embedded in control platform;

(2) Predictive correction block correct the controlled variables' values and Controllability Check block cope with freedom information;

(3) Global linear programming (GLP) block gathers all the all controlled variables (CVs) and manipulated variables (MVs) and makes a total optimization according to all the constraints;

(4) Dynamic optimal block accepts the optimal outputs resulted from the GLP as set-points and runs as a standard horizontal optimization algorithm;

(5) The results (MVs) from dynamic optimal block will be sent back to runtime database (platform), and another control cycle will begin from step 1 again.

The general model of the reheating furnace is a six-inputs-six-outputs system. Constraints in the system include the limit of furnace temperature, the limit of temperature change in a computation period, the limit of fuel flux, the limit of change ratio of air to gas, *etc.* The change of furnace air pressure can be regarded as disturbances.

In MCC, the optimization index is defined as:

$$\min J(k) = \|\boldsymbol{T}_r(k) - \boldsymbol{T}_P(k)\|_Q^2 + \|\Delta \boldsymbol{u}_M(k)\|_R^2 + \|\boldsymbol{u}_M(k)\|_S^2$$
$$\text{s.t. } \boldsymbol{u}_{\min} \le \boldsymbol{u}_M(k) \le \boldsymbol{u}_{\max}, \Delta\boldsymbol{u}_{\min} \le \Delta\boldsymbol{u}_M(k) \le \Delta\boldsymbol{u}_{\max} \quad (4)$$

where J is the evaluation function of the QP optimization; $\boldsymbol{u}_M$ the vector of manipulated variables values, here is values of the fuel flux; $\Delta\boldsymbol{u}_M$ the vector of change values of the fuel flux; $\boldsymbol{T}_r$ the values of temperature reference trajectories, the outputs of the ACC model; $\boldsymbol{T}_P$ the vector of controlled variables prediction values, here is the temperature predictions.

3.1 Particular features of MCC

(a) Using global linear programming (GLP) in global optimization and dealing with total constraints. In order to resolve a maximization economic evaluation during the horizontal optimization, the evaluation function must be changed into $J' = J + E(U, T)$. Here, $E(U, T)$ is the economic evaluation by means of MVs and CVs. In most cases, the economic evaluation and other constraints can be expressed into a linear optimization problem (LP). Comparing with QP, the solution of LP becomes much simpler and timesaving.

(b) Introducing ideal resting value (IRV) control mode in the control of MV. To economize the energy and material used in process, MCC also takes IRV mode as the optimal set-points of MVs when there is redundant freedom in the control task.

(c) Advancing ZONE control mode in the treatment of the freedom of control system. There are two kinds of control modes in MCC-ZONE control mode and SETPOINT control mode. The ZONE control mode is satisfied by making the variable's value floating between a high and low limits with much more freedom than the SETPOINT control mode which is fulfilled by setting the variable's value on a strict bounds around the setting value. These two kinds of control modes can switch into each other based on the freedom and priority information of each variable.

3.2 Setting of optimization index

The optimization index can be set according to different control requirements. If the temperature tracing accuracy is demanded for high-qualified productions, $\boldsymbol{Q}$ is to be set larger. If the energy saving demand is more important, the $\boldsymbol{Q}$ can be set smaller where $\boldsymbol{R}$, $\boldsymbol{S}$ are set larger accordingly, which results the smoother fuel flux.

In the optimization index, the temperature tracing error, the fuel flux value and its changes are taken into account explicitly. All these values can be regulated to reach specific requirements by modifying corresponding weight matrix. Taking the fuel flux change into account in the performance index is useful to make the fuel flux changes smoother, for large fluctuation of fuel flux is harmful to the combustion in the furnace. With the optimization index, it is obviously to see that the accuracy of temperature tracing and the values of fuel flux can be adjusted simultaneously in a systematical way.

In spite of handling input and output constraints explicitly, the MCC controller make decoupling implemented naturally for its multivariable handling abilities. From a practical viewpoint, these features can great enhance the performance of the reheating furnace.

4 Numerical results

The simulation result of the constructed control system will be shown to demonstrate the effect of the proposed control strategy. In this system the initialization is realized by reading recorded data from industry site. Hence, the initial condition is the same as the real system. MCC controller and traditional PID controller are used and the simulation results are figured. The parameters of PID controller are the same as the real plant. Because setting of the optimization index of MCC is for temperature tracing accuracy requirement, so the matrix $\boldsymbol{Q}$ is most important and matrix $\boldsymbol{R}$, $\boldsymbol{S}$ are set for slight changes requirement of fuel flux.

The simulation covers 5 h. Here only show one simulation result. The temperature tracing results of preheating and heating zone is listed in **table 1**, with no change of the controller parameters of PID and MCC. The two zones include four manipulated variables and four controlled variables, which are tightly coupled.

Table 1 Temperature tracing result of the reheating furnace

Zone	Temperature range / ℃	Max error / ℃		Absolute average error / ℃	
		PID	MCC	PID	MCC
Preheating lower zone	1026-1190	83.2	39.6	29.9	12.3
Preheating higher zone	1034-1200	76.1	42.3	32.1	17.8
Heating lower zone	1174-1310	81.7	40.2	31.0	15.1
Heating higher zone	1193-1325	71.5	37.6	21.3	14.3

Figure 4 shows that the temperature controlled by conventional PID controller can follow the set-points when the set-points change slowly, but it will oscillate when the set-points has a large change. MCC controller enables the furnace temperature follows the set-points almost exactly, no matter whether the set-points have change. The control performance of MCC controller is much better than that of PID controller.

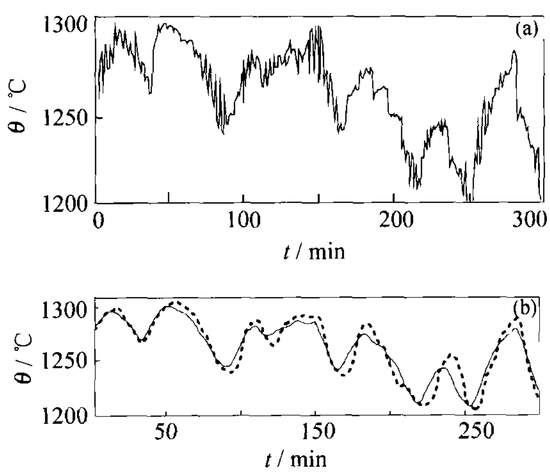

Figure 4 The furnace temperature in the heating lower zone, (a) the solid line is the set-points; (b) the solid line is the temperature obtained from loops with MCC controller, the dotted line is the temperature obtained from loops without MCC controller (Only PID controller is used).

The fluctuation of the fuel flux has significant impact on the value of residual oxygen content, an important index for combustion analysis in the furnace. Lower value of residual oxygen content means more sufficiently fuel combustion and more energy saving. Because MCC can regulate the fuel flux by change corresponding weight matrix in the on-line optimization, it is also an ideal energy saving technique.

In **figure 5**, the fuel flux provided by loops with MCC controller is much smoother than that provided by loops without MCC controller. The fuel flux provided by loops with only PID controller has a large oscillation when set-points of furnace temperature change.

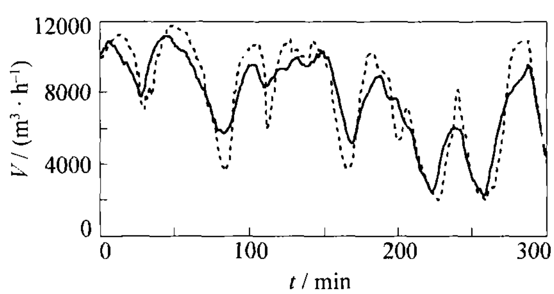

Figure 5 The fuel flux in heating lower zone, the solid line is the fuel flux obtained from loops with MCC controller, the dotted line is the fuel flux obtained from loops with PID controller.

The results in table 1 show that the tracing accuracy is largely improved by using MCC controller. The reason is that MCC is based on multivariable control strategy, where the decoupling work is implemented in a systematical and implicit way. That is why advanced control becomes more and more important in complex multivariable industry process.

5 Conclusions

(1) A better temperature tracing accuracy is obtained compared with the result of a traditional controller.

(2) The implemented strategy is a kind of optimization method and some energy saving techniques can be designed accordingly.

(3) The fluctuation of fuel flux is taken into consideration in the optimization index explicitly, so gas combustion in the furnace will be more exhaustive. Energy saving means more profits to steel plants.

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