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Optimization of temperature setpoints in combustion control

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Abstract: A method was developed to set the optimal setpoints of temperature through adjusting the temperature-rising-ratio (TRR) of preheating to heating zone. In addition, control loops were built to validate the effect of the proposed method. The calculation of optimal setpoints was a repeating procedure and could compensate the uncertainty of furnace. It is shown that the heating system obtained via this method can reduce the fuel consumption to some extent and the heating quality can be guaranteed as well.

Key words: temperature control; weighted average; energy saving; temperature-rising-ratio (TRR)

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燃烧控制中温度设定的优化

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摘要：提出一种通过调节钢坯在预热段和加热段的温升率来设定预热段和加热段的最优设定温度的方法,并且实现了提出的算法.在提出的方法中,最优温度的设定是一个重复过程,即在每个计算周期都进行计算.这样可以最大限度的消除系统的不确定因素的影响从而保证设定温度的最优.通过文末的仿真及提供的数据可以看出本方法可以在一定程度上保证加热质量同时达到节能的目的.

关键词：温度控制；加权平均；节能；温升率

1 Introduction

Reheating furnaces consume much energy in the production. To save energy, many researchers tried to reduce energy consumption and improve the efficiency of furnace[1~5]. These researches mainly depended on precise models, which are difficult to obtain in practice. Facco G et al built air-to-fuel ratio setting curves to guarantee the optimal combustion for different velocity of fuel flow[6]. Yang proposed multi-model determination approach, which takes the diversity of furnace states and requirements of control into account to reach energy saving goal[7].

In this paper, we focus on how to get setpoints of temperature in automatic combustion control (ACC). Currently, the setpoints of furnace temperature are calculated according to a constant temperature-rising-ratio (TRR) of preheating zone to heating zone. This is not reasonable especially when the state of milling line is not steady or the charging temperatures of slabs have great changes. Unfortunately, the two cases often occur in practice, which requires a new method to solve the problem. Our proposed method adjusts the TRR of preheating zone to heating zone in each computation to get the optimal temperature trajectory of each slab and obtain the optimal temperature setpoints of each zone. Consequently, the energy-saving goal can be realized online.

2 Problem description

The structure of the reheating furnace is shown in Fig.1. It is divided into 4 zones: tail, preheating, heating and soaking zone. The last three zones are further divided into upper zone and lower zone.

Our objective is to get the optimal setpoints of furnace temperature of preheating upper and lower zone, heating upper and lower zone, soaking upper and lower zone to

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reduce the expenditure of energy in heating process.

According to the energy balance, the heat energy generated by combustion can be divided into three parts: energy absorbed by slabs, energy taken away by waste gas, and energy lost in radiation, heat conduction in walking beam and various leakage of furnace. The last part is determined by the structure and material of furnace and cannot be reduced for a certain furnace. We will focus on how to decrease the energy taken away by waste gas and, at the same time, increase the energy absorbed by slabs.

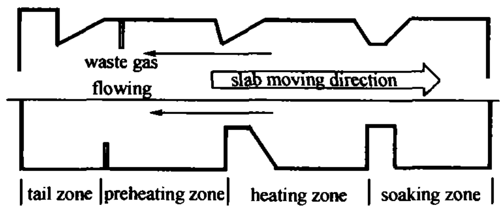


Fig. 1 Structure of furnace

In the proposed method, the optimal temperature trajectory of each slab is calculated according to the slab distribution in the furnace, the state of furnace and milling line. The optimal temperature trajectory is a heating curve. If the slab is heated according to this curve, the heating quality of slabs can be guaranteed and energy can be saved. The difficulty lies in how to adjust the optimal temperature trajectory according to the changing states of furnace and milling line so that the influence of these changes can be compensated. The optimal trajectory can be illustrated in Fig. 2. From Fig. 2, it can be clearly seen that the optimal trajectory is closely related to TRR of preheating zone to heating zone, which is denoted as and can be calculated as:

α = (temperature increment in unit time at preheating zone) / (temperature increment in unit time in heating zone).

For a certain slab in preheating zone, the discharging temperature is predefined and its current temperature can be calculated. α can be regulated by adjusting the slab temperature at the exit of preheating zone. Hence, our objective changes to regulating α to decrease furnace temperature setpoints as much as possible under the condition that the heating quality of slabs can be guaranteed. This objective is the same as the original one.

Since the flow direction of the waste gas in the furnace is from soaking zone to tail zone and the flue of the waste gas is located at tail zone, which is close to preheating zone, the higher the preheating zone temperature, the more fuel consumed in this zone and the more combustion energy will be taken away by waste gas. So, in the heating process, the temperature of preheating zone cannot be too high. To decrease the energy taken away by waste gas, the temperature of preheating zone must be decreased while the temperature of heating zone must be increased first. That is, part of the heating load of preheating zone is transferred to heating zone.

In current practical application, the ratio α always equals to 1. This is based on the assumptions that the slabs have low charging temperature and the furnace state is steady. Moreover, this has the advantage of easy computation. However, it is not reasonable for slabs to have high charging temperature and cannot deal with the case of changing mill pacing. For example, for slabs with high charging temperature, the enter-zone-temperature of preheating zone (the slab temperature when slab moves into preheating zone) are high while exit-zone-temperature of heating zone (the slab temperature when slab moves out from heating zone), which is subject to the constraints of temperature balance of slab and has no change. As a result the exit-zone-temperature of preheating zone will be very high, which requires a high temperature setpoint of preheating zone, and the fuel flux of preheating zone will increase. Since slabs have high charging temperature, the quantity of energy absorbed in preheating zone is limited and most heat energy will be taken away by waste air. Hence, the optimal trajectory of this kind of slabs should be adjusted to prevent the temperature rise in preheating zone while increase the temperature in heating zone. This will increase furnace temperature setpoint of heating zone. Although the heating energy taken away by waste gas flows from heating zone will increase in this case, this waste gas can heat the slabs in the preheating zone.

In this discussion, the tail zone and the soaking zone are not taken into account. The reason is that the tail zone is not a controlled zone and the slabs in this zone is heated by waste gas. In addition, the main function of soaking zone is not to heat the slabs but to balance the inner temperature and surface temperature of slabs. The setpoint of furnace temperature with this zone is subject to the constraints of heating quality and cannot be adjusted with this method.

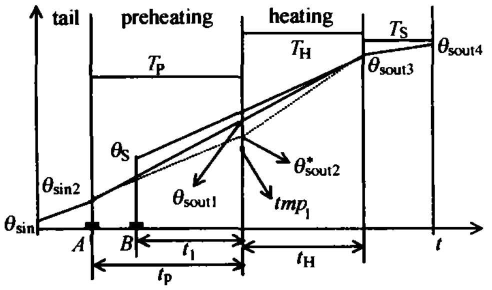


Fig. 2 Optimal temperature trajectory of slab

3 Proposed method

In the following description, the furnace with the structure shown in Fig. 1 will be discussed. For a furnace with more zones, the method is valid too.

As shown in Fig.2, when a slab moves into preheating zone (at point A), its charging temperature is θ_{sin1} and target temperature is θ_{sout4}, the enter-zone-temperature of preheating zone, namely the slab temperature at this time instance, is denoted as θ_{sin2}, exit-zone-temperature of heating zone is determined by the constraint of temperature balance and denoted as θ_{sout3}. From θ_{sin2}, θ_{sout3}, $\alpha = 1$, the exit-zone-temperature of preheating zone θ_{sout2} can be calculated as follows.

$$\theta_{sout2} = \theta_{sin2} + \frac{\theta_{sout3} - \theta_{sin2}}{t_p + t_H} \cdot t_p, \qquad (1)$$

where t_p and t_H are predictive time that the slab will be heated in preheating and heating zone respectively. θ_{sout2} is the exit-zone-temperature of preheating zone under the condition that $\alpha = 1$.

At the same time, from the furnace temperature of heating zone T_H, the predictive slab heating time in heating zone t_H, and exit-zone-temperature of heating zone θ_{sout3}, exit-zone-temperature of preheating zone θ_{sout2} can be calculated. That means a slab with θ^*_{sout2} can be heated to θ_{sout3} with the mentioned condition. Thus, θ^*_{sout2} can be regarded as optimal exit-zone-temperature of preheating zone.

In heating process, the average heat conductivity of slabs in heating zone, which is denoted as α_H, can be calculated as follows:

$$\alpha_H = c \cdot [(T_H + 273)^2 + (\theta^o_{sout2} + 273)^2] \cdot [(T_H + 273) + (\theta^o_{sout2} + 273)]. \qquad (2)$$

The exit-zone-temperature of heating zone is

$$\theta^N_{sout3} = T_H + (\theta^o_{sout2} - T_H) \cdot \exp(-\alpha_H \cdot t_H), \qquad (3)$$

where c is a constant, θ^o_{sout2} is the slab temperature at the exit of preheating zone, T_H is the furnace temperature of heating zone, and t_H is the predictive heating time in heating zone.

The solution of θ^*_{sout2} can be easily obtained through difference function. Because of restriction of heating capacity, for a certain slab with exit-zone-temperature of heating zone known as θ_{sout3}, the exit-zone-temperature of preheating zone can not stay below a certain value, say $tmp1$, to make sure that the slab can be heated to θ_{sout3} at the exit of heating zone. Hence, the solution of θ^*_{sout2} must be in the interval $[tmp1, \theta_{sout3}]$.

Now, let us determine θ^*_{sout2}. Let $\theta^o_{sout2} = tmp1$ and substitute it into equations 2 and 3, the solution can be denoted as θ'_{sout3}. Comparing θ'_{sout3} with θ_{sout3}, if θ'_{sout3} is higher than or equal to θ_{sout3}, then θ^o_{sout2} can be regarded as θ^*_{sout2}. If θ'_{sout3} is lower than θ_{sout3}, then let $\theta^o_{sout2} = tmp1 + \Delta T$ and substitute into equations 2 and 3 again to get a θ'_{sout3}. This procedure is repeated until θ'_{sout3} is higher than or equal to θ_{sout3}. and this θ^o_{sout2} is regarded as θ^*_{sout2}. In this way, the θ^*_{sout2} can be determined. Generally, the interval $[tmp1, \theta_{sout3}]$ is small and equation 2 and equation 3 are simple, and it is easy to get θ^*_{sout2} online.

To save energy as much as possible, we take θ^*_{sout2} as the slab exit-zone-temperature of preheating zone. Then the TRR at this moment is

$$\alpha = \left(\frac{\theta^*_{sout2} - \theta_{sin2}}{t_p}\right) / \left(\frac{\theta_{sout3} - \theta^*_{sout2}}{t_H}\right). \qquad (4)$$

In the case of the heating quality, since θ^*_{sout2} is a predictive value under current state, if we take θ^*_{sout2} as the exit-zone-temperature of preheating zone, the heating quality of slabs may be affected due to the change of furnace state. To make the algorithm robust, we change θ^*_{sout2} into θ'_{sout2}.

$$\theta'_{sout2} = \theta^*_{sout2} + \lambda \cdot (\theta_{sout2} - \theta^*_{sout2}),\ \lambda \in [0,1] \qquad (5)$$

and TRR changes to

$$\alpha = (\frac{\theta'_{sout2} - \theta_{sin2}}{t_P})/(\frac{\theta_{sout3} - \theta'_{sout2}}{t_H}). \quad (6)$$

Next, those slabs that have been in preheating zone will be considered. Suppose the slab mentioned above moves to point B, the slab temperature is θ_s, which is different from the predictive temperature at point A. The calculation is the same and the temperature-rising-ratio changes to

$$\alpha = (\frac{\theta'_{sout2} - \theta_s}{t_1})/(\frac{\theta_{sout3} - \theta'_{sout2}}{t_H}). \quad (7)$$

Because slabs cannot emit heat energy during heating process, θ'_{sout2} can not be lower than slab current temperature θ_s. That is, if θ'_{sout2} is lower than θ_s, let $\theta'_{sout2} = \theta_s$. This may happen to slabs with high charging temperature.

After the calculation of α of each slab in preheating zone, the compensation of furnace temperature can be obtained according to equation 8.

$$\Delta T_P = (\alpha \cdot t_P^2 \cdot X + Y)/(-\alpha \cdot \frac{\partial \theta^o_{sout3}}{\partial T_P} \cdot t_P^2 - \frac{\partial \theta^o_{sout2}}{\partial T_P} \cdot t_H^2), \quad (8)$$

$$Y = -(\theta^o_{sout2} - \theta^o_{sout1}) \cdot t_H^2 + \alpha(\theta^o_{sout3} - \theta^o_{sout2}) \cdot t_P^2, \quad (9)$$

$$X = \vartheta_{aim} - \Delta\theta_s - \theta^o_{sout3}, \quad (10)$$

where ΔT_P is compensation value of temperature of preheating zone. θ_{aim} is the target temperature and $\Delta\theta_s$ is the restriction value of temperature balance. t_k is predictive heating time in preheating zone or heating zone based on its subscript.

Then, the setpoints of preheating zone at this time instance $T_{Sp}(k+1)$ can be calculated according to furnace temperature of preheating zone at last time instance $T_p(k)$ and the compensation value of preheating zone as in equation 11.

$$T_{Sp}(k+1) = T_P(k) + \Delta T_p. \quad (11)$$

The setpoints of heating zone can be calculated in the same way.

The above calculation shows that for each slab in preheating, a setpoint of preheating zone can be obtained and for each slab in heating zone, a setpoint of heating zone can be obtained too. Since slabs in the furnace have different conditions and different α, the calculated setpoints of preheating zone and heating zone $T_{Sp}, T_{Sp2}, \cdots, T_{Spk}, T_{Sh1}, T_{Sh2}, \cdots, T_{Shk2}$ are different. The final setpoint of preheating zone and heating zone should be the optimization of these temperatures. The objective of this optimization is defined as follows:

$$J = \min\ (a \cdot \sum_{i=1}^{k}(\theta_i - \theta_{aim})^2 + b \cdot \sum_{j=1}^{k} F_j) \quad (12)$$

where θ_i is the predictive discharging temperature of slabs in the furnace and F_i is the fuel flux of each zone, which are functions of setpoints of each zone.

Since the precise mathematical expression of this objective cannot be obtained in practical application, an expert system is constructed to assign weighting factors to the calculated setpoints and the final setpoint of preheating and heating zone will be calculated by weighted average. This method cannot guarantee the optimization, but the rulebase can be adjusted to get a solution near optimization.

Next, the control loops are designed to ensure that the furnace temperature can reach the setpoints. The main control loops include furnace temperature loops and the fuel flux (gas flux and air flux) loops of six zones. The furnace temperature and fuel flux loops form cascade control loops. The steady state and performance of these control loops have a direct influence on the heating quality of the slabs. In the current system, the loop controllers are conventional PID controller. To validate the effect of energy saving of the proposed method, the control loops of the furnace are built and the parameters thereof are identical to the real system. In addition, a system model is built to simulate the combustion process in the furnace[8]. The model of the furnace is built based on energy balance.

The cascade temperature control loop is shown in Fig.3.

In Fig.3, the outer loop is the temperature control loop. ACC provides the optimal temperature setpoints of each zone. The inner loops are the fuel flux control loop. The output of outer loop is sent to cross limit, which is not shown in Fig.3, and the cross limit provides the setpoints of fuel flux. The valves of air and gas are regarded as a first-order system with time delay. The time-constant and time delay of the valves can be measured.

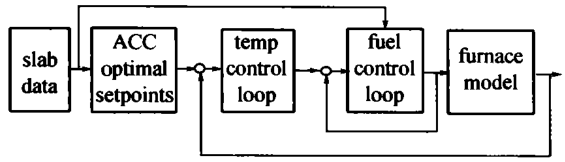
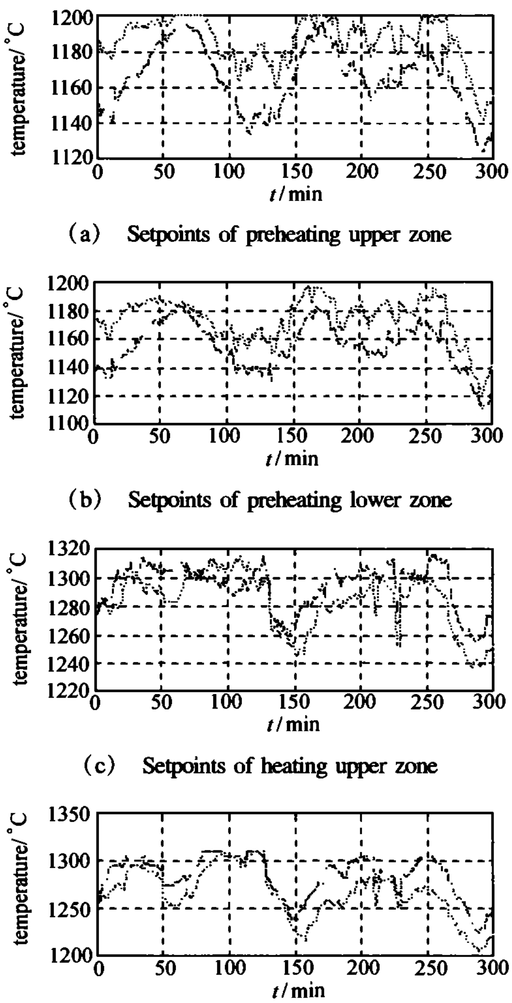


Fig. 3 Structure of control loops

4 Application results

In this section, we calculate the setpoints of furnace temperature with the proposed approach. The results of 5 hours are shown in Fig.4. The condition and distribution of slabs, as well as the predictive heating time in each zone are from the real system. λ is 0.5 in all the 4 subfigures, the solid line is the setpoints calculated when α = 1 and dash line is the setpoints calculated by optimized α.



(a) Setpoints of preheating upper zone

(b) Setpoints of preheating lower zone

(c) Setpoints of heating upper zone

(d) Setpoints of heating lower zone

Fig. 4 Comparison between setpoints got when α = 1 and setpoints got by proposed method

The heating quality, which is measured by error of discharging temperature and difference between slab inner temperature and surface temperature, and the fuel consumed in both cases is shown in Table 1.

Table 1 Heating quality and fuel consumed

	value without optimization	value with optimization
average temperature error	6.38	6.87
average temperature balance error	22.5	24.3
fuel consumed	16031912	14551714

From the comparison, it is clearly seen that the setpoints of preheating zone temperature obtained with our method is lower than setpoints when α = 1 and the setpoints of heating zone temperature obtained with our method is higher than setpoints when α = 1. This indicates that the heating load has transferred from preheating zone to heating zone. The result corresponds to our analysis. In addition, from Table 1, it is safe to say that the heating quality of slabs can be guaranteed and the energy consumed can be saved to a certain extent. That is, the proposed method is valid and reasonable.

5 Conclusion

In the paper, a new method to determine the setpoints of furnace temperature to reach an energy-saving goal is developed. In this approach, through adjusting TRR of preheating to heating zone, the heating load is transferred from preheating zone to heating zone. Each slab in preheating zone is calculated separately to take different conditions of different slabs into account. At the same time, this calculation is carried out repeatedly at each period to compensate the uncertainties of slabs, furnace, and milling line. The results show that this method is valid and its energy saving effect is obvious.

References:

[1] MISAKA Y, TAKAHASHI R, SHINJO A, et al., Computer control of a reheat furnace at kaahima steel works' hot strip mill [J]. *Iron & Steel Engineering*, 1982, 95(5): 51-55.

[2] WANG H. Mathematical model for optimized heating of reheat furnace [J]. *Research on Iron & Steel*, 1992,5:48-51.

[3] DIRK S F J. Online slab temperature calculation and control [A]. *Proc of ASME Int Mechanical Engineering Congress and Exposition* [C].[s.l.]:[s.n.], 1996.

[4] YOSHITANI N, UEYANMA T, USUI M. Optimal slab heating control with temperature trajectory optimization [A]. *Proc of the 20th Int Conf on Industrial Electronics, Control and Instrumentation*

[C].[s.l.]:[s.n.], 1994.

[5] YANG Y, PAN D. Optimal furnace temperature distribution and control of a circular reheating furnace [J]. *Control Theory & Applications*, 1993, 10(3):307 - 315.

[6] FACCO G, PETERSEN M E, SCHURKO R J, et al. State of the art slab reheating furnace at Dofasco [J]. *Iron and Steel Engineering*, 1990, 67(1):27 - 36.

[7] YANG Y, LIANG J. Multi-model control of reheat furnace [J]. *Metallurgical Industry Automation*, 1991, 15(5):15 - 19.

[8] XU Liyun, ZHANG Bin, WANG Jingcheng, et al. Online simulator of reheating furnace based on mathematical model [J]. *Control and Decision*, 2002, 3(7):207 - 210.

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8月10日晚举行了新一届控制理论专业委员会成立以来的第一次全体委员工作会议,参加会议的30多位委员皆出席了会议.在会上,程代展主任先向大家通报了专业委员会成立以来的工作情况及明年会议的筹备情况,并请上海交通大学李少远教授具体汇报承办工作的进展,然后讨论了有关控制理论专业委员会及中国控制会议今后的工作.委员们积极响应对加强专业委员会工作及中国控制会议的国际化的设想,赞同本次会议在加强国际化与规范化方面作出的努力,并提出许多建设性意见.最后会议讨论了2005年中国控制会议的申办问题.截止到2003年8月10日专业委员会收到了四川大学和华南理工大学申办2005年中国控制会议的书面申请,会上又有哈尔滨工业大学和华中科技大学提出口头申请,专业委员会对大家的积极申办表示热烈的欢迎和衷心的感谢.为使申办工作有序进行,本次会议进一步具体规范了中国控制会议的申办程序:明确申办单位需提前两年向专业委员会提交正式书面申请材料,截止时间为当年中国控制会议召开的前一周,在当年中国控制会议专业委员会全体与会委员会议上讨论决定两年后会议的承办单位.依此程序,会议最后决定2005年由华南理工大学承办第24届中国控制会议.

8月12日下午举行2003年中国控制会议闭幕式及《关肇直奖》颁奖仪式.闭幕式由控制理论专业委员会副主任王龙教授主持.《关肇直奖》评奖委员会主任郑大种教授宣布本届《关肇直奖》获奖论文.陈翰馥院士、冯纯伯院士向获奖者颁发证书和奖金.随后,控制理论专业委员会副主任郑大种教授代表控制理论专业委员会做大会总结,他感谢中国科学院系统科学研究所、三峡大学电气信息学院为会议成功所做的卓越工作和巨大努力,感谢中国技术创新有限公司对关肇直基金的赞助,感谢浙江天煌科技实业有限公司和固高科技(深圳)有限公司对大会的赞助.最后,上海交通大学李少远教授邀请大家积极参加明年在无锡召开的下一届(23届)中国控制会议.

本次会议本着严谨求实、开拓创新、积极进取的精神,在加强会议的国际化、学术性和规范化方面进行了许多积极的努力.会议的总体学术水平和组织工作受到国内外与会代表的高度评价,认为是近年来学术水平较高的一次.会后代表们游览了美丽的大小三峡和雄伟的三峡大坝工程.

中国自动化学会控制理论专业委员会
2003年9月2日