Optimal Heating and Energy Management for the Reheating Furnace Using Oxygen Enhanced Combustion

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Abstract

Oxygen enhanced combustion techniques can be applied to reheating furnaces by reducing nitrogen of combustion air, either partially or completely, for reducing gas emissions and improving the thermal efficiency and productivity. However, with the increase of the oxygen concentration, the furnace temperature and the heat transfer characteristic are different from conventional air combustion, and the heating process of billets in the furnace will be affected, which is a challenge to the optimized control of the reheating furnace.

The optimization of the furnace temperature system is the basis of optimized control. In this paper, the dynamic model and furnace temperature optimization model were established. According to the mathematical model steady quantitatively analyze the heating process influence that change of each billet temperature, the furnace temperature of the reheating furnace using oxygen enhanced combustion was optimal analyzed by the object function under various operation conditions. The objective function is the minimization of total process energy consumption per ton of steel. The optimal variables are the oxygen concentration and production rate. Key performance indicators such as temperature uniformity, the discharging target temperature as well as the minimization of steel mass loss and also the minimization of CO₂ emissions to the atmosphere are included in the optimality criteria.

Energy consumption per ton of steel, production rate and thermal efficiency of furnace in various levels of oxygen enrichment were investigated by comparing with baseline furnace (21 % of O₂ in air). The results showed that the best range of oxygen enrichments was between 21% and 45% by volume, as the higher slope of energy consumption decrease and production increase occurs in this range.

Keywords: optimal heating, energy management, reheating furnace, oxygen enhanced combustion

Introduction

The impact of climate change is becoming increasingly evident, posing significant challenge, both in the political and scientific arenas. The emission of greenhouse gases has been reported to be the main cause of global warming.¹,² To mitigate impacts, carbon dioxide capture and storage (CCS) is expected to play significant role. Since power plants, transportation, cement, metallurgical industries among others constitute the largest source of greenhouse gas emission,³ it becomes vivid why technology research is focused on capturing CO₂ emissions from stationary sources. Three key technologies are currently available for CCS: post-combustion capture technology, pre-combustion capture technology, and oxyfuel combustion technology. In this work, oxygen enhanced combustion technology contains the best features of both oxyfuel and post-combustion capture, as seen in the Figure 1. Oxygen enhanced air combustion is a viable technology for carbon capture and storage providing CO₂ enhanced flue gas that will reduce the size of the carbon dioxide separation unit (CSU). The reduced level of oxygen enrichment compared to pure oxyfuel combustion also reduces the potential size of the air separation unit (ASU).⁴ Furthermore, oxygen enhanced combustion can reduce gas emissions from reheating furnace, improve the productivity and thermal efficiency of
such furnaces.\textsuperscript{5}

However, with the increase of the oxygen concentration, the flame temperature, the atmosphere and the heat transfer characteristic are different from conventional air combustion, and the heating and oxidation process of billets in the furnace will be influenced. The uniformity of temperature through the billets affects the quality of the metal sheet and the scale on the billet surface hinders heat transfer causing the loss of energy and of material as oxides. Thus, it is very important to control the furnace temperature and the oxygen concentration.

Because of high nonlinearity, large time delay, large time-constant and various uncertain factors, the modeling and reliable control of a reheating furnace is always a challenging problem.\textsuperscript{6} During the past decade, the challenge has attracted considerable attention and a significant progress has been made in the furnace control.\textsuperscript{7-10} The heat exchange in the furnace is very complex and many limitations and assumptions need to be considered, this leads to the fact that different researchers treat the furnace in a different way and different methods developed.

In this paper, a complete model of reheating furnace will be constructed. The heat conduction model describes the heating process of the billets. The steady state optimization model gets the set-points of the furnace temperature. The scale formation model describes the influence of the atmosphere on the oxidation process of billets. The furnace heat balance equation describes the relationship between fuel flux of each zone and operating conditions. Then, these sub-models are connected and the relationship among them is described. Moreover, to improve the performance of the furnace control, a dynamic correction model with constraint control strategy is employed in the furnace temperature optimization model. The results show that the strategy is very satisfactory.

\textbf{Figure 1.} Reheating Furnace of Oxygen Enhanced Combustion with ASU and CSU

\textbf{Figure 2.} Configuration of the Reheating Furnace

\textbf{Mathematical Formulation}

The structure of a reheating furnace is depicted in Figure 2. As seen in the figure, the billet reheating furnace consists of three chambers: preheating, heating, and soaking zones. The billets are fed to the preheating zone and slowly moved through heating and soaking zones, sequentially. The billets are heated to the target temperature roughly in the preheating and heating zones and are
soaked in the soaking zone to retain the uniform temperature through the billets, which are mainly heated by radiative heat transfer of surrounding gas. Thus, in this study, a dynamic model is established, focusing on the dynamic behavior of heat transfer and furnace temperature optimization.

**Model of Heat Conduction**

Typically, for a billet in a reheating furnace, the billet’s length is large compared with its width and gauge. This implies, in turn, that heat transfer along the length direction almost plays no part in contributing temperature uniformity inside the billet. Therefore, it is proper to assume that heat transfer in the billet essentially pertains to two-dimensional behavior. Meanwhile, the effect of water cooled skids on the billet temperature is ignored in that the skid area is small when compared with the billet surface. Accordingly, the heat conduction or heat flow inside a billet can be described by a transient, two-dimensional diffusion equation.

\[
\rho(T)C(T) \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x} [\lambda(T) \frac{\partial T}{\partial x}] + \frac{\partial}{\partial y} [\lambda(T) \frac{\partial T}{\partial y}] \tag{1}
\]

where, \( \rho \), \( C \) and \( \lambda \) are density, heat capacity, and conductivity of the billet, respectively. They are the function of the billet temperature \( T \).

The aforementioned equation is subject to the following initial and boundary conditions:

**Initial condition**

\[
T(x, y)|_{\tau=0} = T_0(x, y) \tag{2}
\]

**Boundary conditions**

\[
x = 0, \frac{\partial T}{\partial x} = 0, \quad x = \frac{a}{2}, \lambda(T) \frac{\partial T}{\partial x} = q_s \tag{3}
\]

\[
y = 0, \lambda(T) \frac{\partial T}{\partial y} = q_l, \quad y = b, \lambda(T) \frac{\partial T}{\partial y} = q_u \tag{4}
\]

where, \( a \) and \( b \) are the width and gauge of the billet. \( q_u \), \( q_l \), and \( q_s \) are the heat flux of the upper, lower, and side surface of the billet, respectively.

\[
q_u = C_{gwm} \left[ \left( \frac{T_{g,u}}{100} \right)^4 - \left( \frac{T_u}{100} \right)^4 \right] + h(T_{g,u} - T_u) \tag{5}
\]

\[
q_l = C_{gwm} \left[ \left( \frac{T_{g,l}}{100} \right)^4 - \left( \frac{T_l}{100} \right)^4 \right] + h(T_{g,l} - T_l) \tag{6}
\]

\[
q_s = \beta (q_u + q_l) \tag{7}
\]

where, \( T_{g,u} \) and \( T_{g,l} \) are the temperature of the gas layer immediately adjacent to the billet, \( T_u \) and \( T_l \) are the surface temperature of the billet at any given location, \( C_{gwm} \) is the radiation heat transfer coefficient, \( h \) is the convective heat transfer coefficient, \( \beta \) is the view factor between imaginary plane and side surface of billet. The convective heat transfer coefficient \( h \) for a surface exposed to the combustion gases is calculated using the relation given by Lebedev and Sokolov.11

The equation for calculating radiation heat transfer coefficient is as follows:

\[
C_{gwm} = \frac{\sigma e_g e_m [1 + \phi_{wm} (1 - e_g)]}{\varepsilon_g + \phi_{wm} (1 - \varepsilon_g) (\varepsilon_g + \varepsilon_m - \varepsilon_g \varepsilon_m)} \tag{8}
\]

where, \( \sigma \) : Stephen-Boltzmann constant, \( e_g \) : emissivity of flue gas, \( e_m \) : emissivity of billet, \( \phi_{wm} \) : view factor between furnace wall and surface of billet.

**Model of Steady State Optimization**

This model is used to calculate the optimal furnace temperature preset value of each zone. Based
on the pyrology mechanism, the furnace temperature can be described as the quadratic equation with the furnace length. Since the rolling rhythm is stable in operation, the heating time of the billet is proportional to the furnace length. Thus, the furnace temperature can also be described as the quadratic equation with the heating time of the billet.\(^{12}\)

\[
T_j (\tau) = a\tau^2 + b\tau + c
\]

where, \(T_j (\tau)\) expresses the furnace temperature and \(\tau\) refers to the heating time of the billet.

Eq. (9) must fit the following boundary conditions:

\[
T_{f1j} \leq a\tau_j^2 + b\tau_j + c \leq T_{f2j}
\]

This boundary condition gives the ideal distribution of the furnace temperature on some important position.

Taken into account of requirements of the production technology for the billet heating quality and the energy savings, a quadratic function is established:

\[
J = \frac{1}{2} \left\{ P \left[ T_m (\tau_i) - T_m^* (\tau_i) \right]^2 + Q \left[ T_c (\tau_i) - T_c (\tau_i) \right]^2 + R \int_{\tau_{i}}^{\tau_{i+1}} T_j (\tau)^2 \right\}
\]

where, \(\tau_i\) is the total time for heating the billet, \(T_m (\tau_i)\), \(T_m^* (\tau_i)\), \(T_c (\tau_i)\), and \(T_c (\tau_i)\) are the slab prediction average temperature, the ideal average temperature, surface temperature, and center temperature, respectively. P, Q, R (P, Q>>R) are weighted coefficients that are selected from experiment, and P =1, Q=1, R=0.001.

The aforementioned function provides the technical requirement for heating quality of billets based on the minimum fuel consumption.

As a result, the problem of solving the optimal zone temperature is summed up to determine the optimal parameters \(a^*, b^*, c^*\) while minimizing the object function. With simplex method, it is easy to determine \(a^*, b^*, c^*\), thus the optimal zone temperature is described as:

\[
T_j (\tau) = a^*\tau^2 + b^*\tau + c^*
\]

Once the temperature preset-value at each zone is calculated from the pyrology mechanism model, it will be fine tuned using the information \(\Delta T_{ma}\) from the soft measurement inference module to obtain the optimal furnace temperature preset-value of each zone.

**Model of Dynamic Correction**

Compared with the air combustion, oxygen enhanced combustion makes many disturbances, such as the flame temperature, furnace pressure, and the atmosphere changes (especially the concentrations of CO\(_2\) and H\(_2\)O) and so on, which influence the heat transfer characteristic of the furnace chamber. These disturbances finally make the billet temperature distribution deviate from the ideal heating curve. In this paper, PID regulation is introduced to compensate for these disturbances (as shown in figure 3). In each control cycle, the billet temperature is compared with the expected, so the billet temperature deviation is obtained, then the zone temperature deviation is expressed as:\(^{13}\)

\[
E_j = \frac{\sum_{j=1}^{m} w_j \int_{L_{j1}}^{L_{j2}} e_j(x) dx}{mL_j}
\]

For the \(j\)-th zone, \(E_j\) is the zone temperature deviation, \(m\) is the number of the heated billets in the same zone, \(w_j\) is the corresponding weight coefficient, \(e_j(x)\) is the billet temperature deviation distribution along the length of the furnace, \(L_{j1}\) and \(L_{j2}\) are the start point and end point of the \(j\)-th zone respectively, \(L_j\) is the length of the \(j\)-th zone. The zone temperature deviation \(E_j\) is added to the zone temperature set-point through the PID regulator. As long as the sampling frequency is high enough, the compensation for the disturbances can be continuous.
**Figure 3. Compensation for Zone Temperature Deviation**

The premise of the PID compensation method is that each zone can be controlled separately. But in fact, there are interactions between different zones. In addition, the set-points for different zones influence the billet heating quality differently. So in addition that the steady state optimal set-points for zones are compensated by PID regulator periodically, expert experiences can be applied to modify the set-points according to the billet heating quality.

**Model of Scale Formation**

Scaling is the oxidation layer that is formed at the billet surface. Representing a loss for the steelmaker, scaling has to be kept as low as possible during the reheating process. The mixed (linear-parabolic) oxidation equation controls of scale growth rate in the gas phase and by ionic diffusion through the scale layer (later) can be regarded as serial resistances.  

\[
\frac{1}{K_j} \cdot \frac{\Delta m}{A} + \frac{1}{K_p} \left( \frac{\Delta m}{A} \right)^2 = \tau 
\]

In this equation, \(\Delta m\), \(A\), and \(\tau\) are the steel loss, surface area, and oxidation time of billet, respectively. \(K_j\) and \(K_p\) are respectively the linear and parabolic oxidation constants, which are functions of temperature and heat capacity of billet, the \(O_2\), \(H_2O\) and \(CO_2\) content. Values of \(K_j\) and \(K_p\) have been derived from measured results published in the literature for different \(O_2\), \(H_2O\) and \(CO_2\) contents and temperatures between 700°C and 1300°C.  

This concept would ideally be extended to include the steel composition, i.e. the progressive effect of additions of species such as C and Si, and the effect of heating rate which affects scale morphology and therefore also the rate of scale growth.

**Heat Balance Equation**

The furnace heat balance equation was used to determine fuel consumption. The following model was employed for heat balance.

\[
B_j \left( Q_{fu} \cdot \frac{L_{O_2}}{\varphi_{O_2}} \cdot n \cdot C_a \cdot t_a + C_f \cdot t_f - V_n \cdot C_g \cdot t_g \right) + Q_{m,j} = Q_{w,j} + Q_{o,j} + Q_{s,j} + \sum_{j=1}^{J} BV_n (t_{x,j} - t_{g,j}) 
\]

where, \(B_j\) : fuel flow rate into j-th zone, \(Q_{fu}\) : fuel caloric value, \(L_{O_2}\) : oxygen flow rate demand for fuel combustion, \(\varphi_{O_2}\) : oxygen concentration, \(n\) : air/fuel ratio. \(C_a\), \(C_f\), and \(C_g\) are heat capacity of oxidant gas, fuel, and flue gas, respectively. \(t_a\), \(t_f\), and \(t_{g,j}\) are temperature of oxidant gas, fuel, and flue gas, respectively. \(V_n\) : flue gas generation per unit volume of fuel combustion, \(Q_{m,j}\) : oxidation heat release from billet, \(Q_{w,j}\) : heat absorbed by billet, \(Q_{o,j}\) : heat loss by cooling water, \(Q_{s,j}\) : heat loss form furnace walls, \(Q_{o,j}\) : the rest heat loss.

Given the furnace temperature \(T_f\) in the j-th zone and the heat absorbed by the billet found from heat conduction model, the required fuel supply \(B_j\) for the j-th zone can be calculated using the aforementioned equation. Similarly, the fuel flow rate in all heating zones may be found by solving the appropriate equation of thermal balance for each zone.
Results and Discussion

The furnace hearth is packed with billets of 0.32 m×0.4 m×9 m, a low carbon steel with 0.04% carbon which is frequently used in hot strip mills. Billets move at a speed consistent with the production rate. Nature gas and various level of oxygen enrichment (21% ~ 100%) provide heat for furnace. In the following discussion, the heat transfer characteristics inside billets and energy consumption behavior of the reheating furnace will be investigated.

The computational model was first validated against experiment results which have been done on a walking beam furnace in a rolling mill. As shown in Figure 4, two furnace temperature curves fit very well, and the required deviation across the section and the surface temperature deviation between simulation and experiment are both less than 20°C.

With different oxygen enrichment conditions, the furnace temperature optimization model and dynamic correction model were employed to keep consistent of furnace temperature. The transient distributions of the average surface temperatures as well as the difference ΔT (between surface and center) versus the heating time are plotted in Figure 5. It can be seen that as soon as the billet is charged into the furnace, the temperature difference rises rapidly. With the increase of oxygen concentration, the slope of temperature curve is greater. This arises from the fact that the temperature increase on the billet surface is faster than in the core, and the radiation heat flux enhanced by the concentration of triatomic gases increased.

![Figure 4. Temperature Profiles Gain from Experiment and Simulation](image)

![Figure 5. Temperature Profiles for Various Oxygen Concentration Conditions](image)

![Figure 6. Variation of Fuel and Oxygen Consumption with Oxygen Concentration](image)

![Figure 7. Variation of Productivity and Thermal Efficiency with Oxygen Concentration](image)
Fuel and oxygen consumption per ton of steel are illustrated in Figure 6. The thermal efficiency of furnace is defined as heat absorbed by load divided by heat input of furnace. The furnace thermal efficiency and production gain is shown in Figure 7. The first point (21%) represents common air as oxidizer. With oxygen concentration of the oxidizer enhanced, the volume of oxygen demanded for combustion increase, and the heat loss take away by flue gas decrease. More percentage of heat can be received by the billets, thus, the thermal efficiency increases and fuel consumption per ton of steel decrease.

![Figure 8. Oxidization Ratio for Various Oxygen Concentration Conditions](image)

![Figure 9. Variation of CO₂ Production and Concentration with Oxygen Concentration](image)

Oxygen-enriched combustion improves the heating rate and reduces the billet residence time in the furnace, but under the condition of fixed air-fuel ratio, the excess oxygen concentration in flue gas increases with oxygen concentration of oxidizer, thus billets oxidation is more serious, as seen in Figure 8. Figure 9 shows that the main benefit of the enrichment on post-combustion capture is the reduction of the flue gas flow rate and the CO₂ concentration enhanced, which clearly result in a reduction in the CSU size, introspectively leading to reduced capital cost.

**Conclusions**

(1) Experiments have proved that, with the optimization strategy investigated in this paper, the performance, the drop out temperature of the billet and the deviation across the section are all satisfactory, the billet heating quality is good.

(2) The appropriate level of oxygen enhancement in an existing reheating furnace is between 21% and 45% by volume, as the higher slope of thermal efficiency and production increase occur in this range. Economical consideration may be regarded as a best point of enhancement.

(3) Reduction of energy consumption from 1.18 GJ for baseline furnace (21% of O₂) to 1.08 GJ for 45% of O₂ in oxidizer per ton of steel is a notable achievement for energy saving purposes. If this furnace reheats 2.4 million ton of steel per year, then approximately $6.4 \times 10^6$ m³ of nature gas can be saved every year. As more advanced air separation and carbon dioxide separation technology are developed, oxygen enhanced combustion with post-combustion capture will lead to more significant cost reduction.

**Acknowledgement**

The article was supported by the Fundamental Research Funds for the Central Universities (NO. FRF-SD-12-013A).
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