NUMERICAL ANALYSIS ON EFFECT OF ADDITIONAL GAS INJECTION ON CHARACTERISTICS AROUND RACEWAY IN MELTER GASIFIER

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Abstract

Considering that pure oxygen at room temperature instead of hot air is injected into COREX melter gasifier, a two-dimensional mathematical model at steady state is developed in the current work to describe the effect of the additional gas injection on the characteristics around the raceway in melter gasifier. The results show that a high speed jet with a highest temperature above 3200 K could be found in front of tuyere. In order to decrease the gas temperature in the raceway to prevent the blowing-down caused by tuyere thermal damage, the additional gas, including N₂, natural gas (NG) and coke oven gas (COG) should be injected through the tuyere. Compared with N₂, additional fuel gas injection gives full play to the high temperature reduction advantage of hydrogen. In addition, considering the insufficient hearth heat after injecting NG, an appropriate amount of COG is recommended to be injected for optimizing blast system.

Introduction

The COREX process, which consists of pre-reduction shaft furnace and melter gasifier, is one of most promising alternative ironmaking processes independent from coking coal.[1, 2] As a birthplace of high temperature gas and smelting heat in COREX melter gasifier, the raceway plays an important role in ensuring stable operation of melter gasifier. However, as in the case of blast furnace, the phenomena in the raceway of melter gasifier are extremely complex. It is impossible to directly measure the internal conditions as a result of the harsh conditions in the raceway. Thus the production operation is carried out only based on the manufacturing experience. Despite that the traditional theoretical combustion temperature calculation model could solve the highest gas temperature in the raceway through thermodynamic, it is unable to take into account the dynamics and calculate the gas temperature distribution.[3-5]

Recently, numerical simulation has become a powerful tool that can provide detailed information on the characteristics around raceway. Although lots of studies on the raceway of blast furnace have been undertaken,[6-12] a general description of characteristics around raceway of melter gasifier should be further investigated, considering that pure oxygen instead of hot air is fed into melter gasifier in comparison with blast furnace. Due to the strong heat release of pure oxygen combustion, the theoretical combustion temperature reaches as high as 3273 K, which induces a different temperature distribution around raceway of melter gasifier as compared with that of blast furnace.[3-5] In addition, because of the low pure oxygen flow rate, the blast kinetic energy of melter gasifier raceway is weak. Therefore, the raceway depth of melter gasifier is only about 0.7 m, which is significantly lowers than...
that of blast furnace (about 2.0 m). This will result in that the primary distribution of gas flow around raceway of melter gasifier is also different from that of blast furnace. Based on the above analysis, compared with blast furnace, the melter gasifier raceway shows completely different smelting characteristics. Recently, Pal et al. [13] developed a three-dimensional model of melter gasifier raceway to investigate the effect of tuyere blocking on the gas temperature around the raceway. However, the raceway shape was too simple and the characteristics in the vertical plane of raceway were not considered.

As can be seen from the above introduction, the work related to the characteristics around melter gasifier raceway is limited. In the present work, a two-dimensional mathematical model at steady state is established, with the raceway shape assumed based on the production practice, to describe the characteristics around melter gasifier raceway, including the gas flow, species and temperature distributions. Meanwhile, the effect of non-fuel or fuel gas injection, including N₂, natural gas (NG) and coke oven gas (COG), on the characteristics around raceway is further discussed to optimize the blast system.

Model Formulation

Governing Equation and Chemical Reactions

In this model, both the gas and solid phases are treated as continuous phases using the Eulerian method. The gas and solid flows are solved by a set of two-dimensional steady state Navier-Stokes equations. The general conservation equation for both phases is given by Equation (1) to describe the mass, momentum, energy and species transfer characteristics in the steady state.\(^{14,15}\)

\[
\nabla \cdot (\rho \psi \mathbf{v}) = \nabla \cdot (\rho \Gamma_{\psi} \nabla (\psi)) + S_{\psi}
\]

(1)

In the actual smelting process of melter gasifier, various complicated phenomena, such as the direct reduction of FeO (highly endothermic), solid-liquid heat transfer, Si and other metalloids reactions, occurs in the coke bed, which results in the fact that the temperature of coke bed is much lower than that of raceway. The above phenomena are not considered to avoid increased complexity. In a previous study, the coke bed temperature was only assumed as \(0.8 T_g\).\(^9\) However, in order to take into account the above complex phenomena, a heat sink, which is described by Equation 2, is used in this model.\(^{12}\)

\[
\text{Source}_{\text{coke}} = -h_s A (T_g - T_b)
\]

(2)

\[
T_b = \max(0.75T_g, 1773)
\]

(3)

Therefore, the changes of gas and solid temperature are governed by three physical processes: convection heat transfer, heat transfer associated with mass transfer and heat dissipation in the coke bed resulting from complex phenomena.

The chemical reactions considered in this model are listed in Table I. The heterogeneous reactions, including coke combustion, coke solution loss and water gas reaction, are calculated based on the heterogeneous reaction rate model.\(^{6,8}\) The finite reaction rate model\(^{16}\) is used to simulate the homogeneous reactions, including the combustions of CO, H₂ and CH₄. In order to simplify the model, other possible chemical reactions, as mentioned above, are not considered. According to the above simplified method, ignoring these reactions has little effect on the characteristics around the raceway.
### Table I. Chemical reactions considered in this work

<table>
<thead>
<tr>
<th>n</th>
<th>Chemical reactions</th>
<th>Reaction rates expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C + O₂ → CO₂</td>
<td>( R_n = \frac{A_i}{M_i} \rho_i \frac{1}{k_f} + 1/(\eta k_f) )</td>
</tr>
<tr>
<td>2</td>
<td>C + CO₂ → 2CO</td>
<td>( R_4 = 1.3 \times 10^{11} P_C O P_{O_2}^{1/2} P_{H_2O}^{1/2} \exp(-15100/T_g) )</td>
</tr>
<tr>
<td>3</td>
<td>C + H₂O → CO + H₂</td>
<td>( R_5 = 9.87 \times 10^8 P_{H_2} P_{O_2} \exp(-3.1 \times 10^7 / R T_g) )</td>
</tr>
<tr>
<td>4</td>
<td>CO + 1/2O₂ → CO₂</td>
<td>( R_6 = 2.17 \times 10^{12} P_{CH_4} P_{O_2}^{1/2} \exp(-53670 / R T_g) )</td>
</tr>
<tr>
<td>5</td>
<td>H₂ + 1/2O₂ → H₂O</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>CH₄ + 1/2O₂ → CO + 2H₂</td>
<td></td>
</tr>
</tbody>
</table>

### Numerical Model and Boundary Conditions

The schematic diagram and boundary conditions of model are shown in Figure 1. According to the void fraction, the whole simulation region is divided into three zones. The void fraction of moving bed, deadman and raceway is assumed as 0.35, 0.20 and 0.75 respectively.[12,13] It should be noted that, due to the smaller blast kinetic energy, the raceway void fraction of melter gasifier is slightly smaller than that of blast furnace. The top pressure of moving bed is assumed as the plant pressure. There is no gas flow at the bottom of deadman. In addition, the deadman shape is calculated based on a quartic expression in radial position as indicated in Equation 4.[17] This expression is symmetric about the axis and tangential to the raceway bottom. The raceway is designed as the shape of “balloon” with the depth of 0.7 m, based on the actual measurement.[18] The diameter of tuyere is 0.03 m.[19] The typical plant operating parameters of melter gasifier, as listed in Table II, are used as the boundary conditions.[19-21] As for the wall, the free-slip condition is applied in the wall boundary for the gas phase. At any point along the wall, the energy wall function is used to describe the wall heat loss. Besides, a zero-gradient condition for all species is assumed at walls.[15]

![Figure 1. Schematic diagram and boundary conditions of model](image)

### Table II. Operating parameters of melter gasifier considered[19-21]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting rate</td>
<td>150 t/h</td>
</tr>
<tr>
<td>Fuel ratio</td>
<td>1062 kg/t</td>
</tr>
<tr>
<td>Plant pressure</td>
<td>360 kPa</td>
</tr>
<tr>
<td>Tuyere O₂ Consumption</td>
<td>55665 Nm³/h</td>
</tr>
<tr>
<td>Tuyere O₂ Temperature</td>
<td>300 K</td>
</tr>
</tbody>
</table>
For computational convenience, the assumptions in this model are given as follows. (1) Only the gas and solid burden are considered, while the powder, liquid iron and slag are ignored. (2) According the difference of additional gas injection, the gas considered in this model includes O\textsubscript{2}, CO, CO\textsubscript{2}, H\textsubscript{2}, H\textsubscript{2}O, CH\textsubscript{4} and N\textsubscript{2} in the most complicated situation. (3) The solid burden only includes coke (or char formed by lump coal), with the assumption that it consists of graphite and amorphous carbon, so its effective formation enthalpy is -1.2×10\textsuperscript{7} J/kmol.\textsuperscript{15} (4) The void fraction of moving bed, deadman and raceway is set as constant and instead of changing as the solid descends. (5) The coke flow velocity is fixed, and its residence time inside the deadman is 24 times more than that in the moving bed.\textsuperscript{22}

**Model Validation**

Due to the lack of directly measured data around raceway of melter gasifier, the mathematical model is only validated using the traditional theoretical combustion temperature, as shown in Equation (5). In the current work, the comparison between the highest gas temperature inside raceway from the simulated result and the traditional theoretical combustion temperature is summarized in Table III.

\[
T_f = (Q_{\text{combustion}} + Q_{\text{physical}} - Q_{\text{ASH}}) / (V_g \cdot c_g)
\]

Table III. Comparison between highest gas temperature inside raceway from the simulated result and traditional theoretical combustion temperature

<table>
<thead>
<tr>
<th>Traditional theoretical combustion temperature</th>
<th>Highest gas temperature</th>
<th>Absolute error</th>
<th>Relative error</th>
</tr>
</thead>
<tbody>
<tr>
<td>3966 K</td>
<td>3543 K</td>
<td>423 K</td>
<td>10.7 %</td>
</tr>
</tbody>
</table>

It is noted that their relative error is as high as 10.7 %. The disagreement between the traditional theoretical combustion temperature and the simulated result can be analyzed from the following aspects. On the one hand, the theoretical combustion temperature is defined as the temperature that results from a complete combustion process without any heat loss. Its calculation conditions are too idealistic, so that the calculated value is inevitably higher than the actual value. On the other hand, the theoretical combustion temperature is only calculated through thermodynamic, which is unable to take into account other complex factors such as the dynamics and the gas expansion. However, although the theoretical combustion temperature is not accurate, it is still used to validate this work because of the lack of alternative monitoring method.

Generally speaking, the simulated result is basically consistent with the traditional theoretical combustion temperature, which proves the applicability of the current model for prediction of the characteristics around raceway of melter gasifier.

**Results and Discussion**

**General Features**

Three stages could be observed in the radial distributions of the gas temperature and species along the tuyere level as shown in Figure 2. In the Stage 1, due to the large temperature difference between gas and solid, the gas-solid heat exchange plays a dominant role, and the gas in room temperature is slowly heated up. Meanwhile, the lower gas temperature results in a slow chemical reaction rate, thus the volume fraction of CO and CO\textsubscript{2}...
is nearly 0. In the stage 2, the increasing gas temperature improves the chemical reaction kinetics condition, the coke combustion gradually plays a leading role, the O$_2$ concentration decreases sharply, while the CO$_2$ concentration and the gas temperature increases rapidly and reaches the max value. On the other hand, resulting from the coke solution loss, the CO concentration increases slowly and is slightly smaller than the CO$_2$ concentration. In the stage 3, with the decreasing O$_2$ concentration, the coke solution loss gradually becomes dominant. Thus CO$_2$ concentration decreases, while the CO concentration increases, and the gas heat is rapidly absorbed. In addition, the temperature difference between gas and solid is relatively large, so that the gas-solid heat exchange rate is faster in this stage. Under the combined effects of the above two aspects, the gas temperature decreases and is gradually stabilized.

![Figure 2. Radial distribution of gas temperature and species along tuyere level](image)

**Effect of Additional Gas Injection**

As discussed above, the high gas temperature around the raceway would easily lead to tuyere thermal damage. Therefore, in the actual production, it is necessary to inject additional gas to reduce the gas temperature around the raceway for protecting tuyere under the condition of fixed tuyere oxygen flow rate. Generally speaking, the additional gas could be divided into two types. One type is non-fuel gas, such as N$_2$, which could not combust, and only increase gas flow rate around the raceway. The other type is fuel gas, including NG and COG, which could both combust and increase gas flow rate. The chemical compositions of NG and COG are shown in Table IV. In this section, five volume fractions of additional gas, which varies from 0 to 8% by a 2% step, are selected to discuss the effect of non-fuel or fuel gas injection on the characteristics around raceway.

<table>
<thead>
<tr>
<th></th>
<th>CH$_4$</th>
<th>CO$_2$</th>
<th>N$_2$</th>
<th>H$_2$</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG</td>
<td>97</td>
<td>2</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>COG</td>
<td>28</td>
<td>2</td>
<td>5</td>
<td>58</td>
<td>7</td>
</tr>
</tbody>
</table>

The effect of volume fraction of additional gas injection on the highest gas temperature in the raceway is shown in Figure 3. The volume fraction of N$_2$, NG and COG increases by 8%, with a decrease of about 153 K, 399 K and 220 K in the highest gas temperature in the raceway. Generally speaking, the thermal balance calculation of the melter gasifier shows that the theoretical combustion temperature should be higher than 3200 K, in order to ensure the hearth heat. Therefore, when the COG injection concentration is 8%, the gas temperature in the raceway decreases obviously, which may result in insufficient hearth heat, while the reduction of gas temperature in the raceway, which results from injected N$_2$ and COG, could
not affect the normal smelting production of melter gasifier.

![Figure 3. Effect of volume fraction of additional gas injection on highest gas temperature in raceway](image)

**Optimization of Blast System**

In the actual production, the main problem of the melter gasifier raceway is the serious tuyere thermal damage resulting from the high gas temperature around the raceway. The statistical data shows that the chambering in the front of tuyere, caused by the continuous scour of the high speed and temperature gas, accounts for 80% of tuyere thermal damage. In order to solve this problem, the optimization of blast system should be considered. As discussed above, the additional gas injection could effectively reduce the gas temperature around the raceway to protect the tuyere.

For **N₂**, the non-fuel gas, it not only reduces the gas temperature around the raceway, but also weakens the heat transfer from the gas to the tuyere, resulting from its relatively low thermal conductivity, to further reduce the thermal aggregation in the tuyere. The production practices of China Baosteel show that when the volume fraction of additional N₂ injection is 8% or more, the number of damaged tuyere decreases effectively and the service life of tuyere is prolonged.

For the fuel gas, including NG and COG, their drop of the highest gas temperature in the raceway is far more significant than N₂. Despite that the additional fuel gas injection could replace a part of solid fuel, the hearth heat may be insufficient due to a large amount of gas injection, so that a thermal compensation is necessary. Common methods of thermal compensation for blast furnace includes reducing blast humidity, increasing blast temperature and oxygen-enriched blast. However, pure oxygen at the room temperature instead of hot air is fed into melter gasifier in comparison with blast furnace, so the traditional thermal compensation for blast furnace is unsuitable for melter gasifier. Therefore, the amount of additional fuel gas injection is limited. For example, the volume fraction of additional NG injection should not exceed 6%. More importantly, the additional fuel gas injection could reduce the fuel ratio of melter gasifier to decrease the cost of hot metal. The decreased amount of sulfur from the fuel also improves the quality of hot metal. It is worth noting that the additional fuel gas injection could give full play to the high temperature reduction advantage of hydrogen in the fuel gas, which will promote the indirect reduction of the sponge iron and improve the smelting efficiency. Therefore, the fuel gas, including NG and COG, has a higher value than N₂ to be injected into the melter gasifier.

Compared with NG, the replacement ratio between COG and solid fuel is relatively low. However, considering that the primary resource (NG) is valuable, the secondary resource (COG) has stronger economic benefits to be used as an additional gas.
Conclusion

A two-dimensional mathematical model at steady state is successfully developed to analyze the effect of the additional gas injection on the characteristics around the raceway in melter gasifier. The accuracy of model is evaluated using the traditional theoretical combustion temperature. A sufficient consistency between the simulated result and the theoretical combustion temperature is achieved. Under the current calculation conditions, the results could be summarized as follows. After pure oxygen at room temperature is fed through the tuyere, a high speed jet could be formed. Resulting from the gas-solid heat exchange and the coke combustion, the gas temperature rapidly increases to above 3200 K. Under the condition of fixed tuyere oxygen flow rate, the increased volume fraction of additional gas injection reduces the highest gas temperature in the raceway to prevent the tuyere thermal damage. Compared with N₂, additional NG or COG injection not only replaces a part of solid fuel, but also gives full play to the high temperature reduction advantage of hydrogen in the fuel gas, which improves the smelting efficiency of melter gasifier. However, considering the insufficient hearth heat after injecting NG, the lack of thermal compensation which is used for blast furnace and the effective utilization of secondary resource, an appropriate amount of COG could be injected as an additional gas.

Nomenclature

\[ A_s : \text{Surface area of solid particle, m}^2/\text{m}^3 \]
\[ c_g : \text{Heat capacity of gas formed in front of tuyere, kJ/m}^3\cdot\text{K} \]
\[ h_g : \text{Heat transfer coefficient of gas, W/m}^2\cdot\text{K} \]
\[ k_s : \text{Rate constant of heterogeneous reaction, kg/s} \]
\[ k_f : \text{mass transfer coefficient, kg/m}^2\cdot\text{s} \]
\[ M : \text{Molecular weight, kg/kmol} \]
\[ P, P_i : \text{Pressure, Partial pressure of specie } i, \text{ Pa} \]
\[ Q_{\text{ASH}}, Q_{\text{physical}} : \text{Heat carried by ash, Heat carried by coke and gas, kJ/min} \]
\[ Q_{\text{combustion}} : \text{Combustion heat, kJ/min} \]
\[ R : \text{Gas-law constant, 8.314472 J/mol}\cdot\text{K} \]
\[ R_n : \text{Rate of reaction } n, \text{ kmol/m}^3\cdot\text{s} \]
\[ r_{\text{deadman}} : \text{Distance between bottom of raceway and symmetry, m} \]
\[ S_\psi : \text{Source term for variable } \psi \text{ in Equation (1), various} \]
\[ T_f, T_g : \text{Theoretical combustion temperature, Temperature of gas phase, K} \]
\[ V_g : \text{Volume of gas formed in front of tuyere, Nm}^3/\text{min} \]
\[ \bar{v}_j : \text{Physical velocity of phase } j, \text{ m/s} \]
\[ y_{\text{deadman}} : \text{Height of deadman at symmetry, m} \]
\[ \varepsilon_j : \text{Volume fraction of phase } j, - \]
\[ \rho_j : \text{Density of phase } j, \text{ kg/m}^3 \]
\[ \Gamma_\psi : \text{Diffusion coefficient for variable } \psi \text{ in Equation 1, various} \]
\[ \psi : \text{General dependent variable in Equation 1, various} \]
\[ \omega_i : \text{Volume fraction of specie } i \text{ in gas phase, -} \]

References