Research Article

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Numerical Analysis on Effect of Additional Gas Injection on Characteristics around Raceway in Melter Gasifier

<https://doi.org/10.1515/htmp-2019-0042>

Received Mar 11, 2019; accepted Jul 01, 2019

Abstract: The raceway plays an important role in the mass and heat transportation inside a melter gasifier. Considering that pure oxygen at room temperature instead of hot air is injected into the 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 3500 K could be found in front of tuyere. Furthermore, a small scale of gas flow circulation occurs in front of tuyere that results in a more serious thermal damage to tuyere. In order to decrease the gas temperature in the raceway to prevent the blowing-down caused by tuyere damage, the additional gas, including N_2 , natural gas (NG) and coke oven gas (COG) should be injected through the tuyere. Compared with N_2 , 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 and the effective utilization of secondary resource, an appropriate amount of COG is recommended to be injected for optimizing blast system.

Keywords: melter gasifier raceway, additional gas injection, characteristics, mathematical model

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Nomenclature

A_s	Surface area of solid particle, m^2/m^3
C_1, C_2	Turbulent model constants, -
c_g	Heat capacity of gas formed in front of tuyere, $kJ/m^3 \cdot K$
$\bar{F}_{gs}$	Gas-solid drag force, N/m^2
G_k	Turbulence production due to viscous force, $kg/m \cdot s^3$
$\vec{g}$	Gravitational acceleration, m/s^2
ΔH_n	Interphase heat source for reaction n , $J/kmol$
h_{gs}	Heat transfer coefficient between gas and solid, $W/m^2 \cdot K$
h_g	Heat transfer coefficient of gas, $W/m^2 \cdot K$
k	Turbulent kinetic energy, m^2/s^2
k_c	Rate constant of heterogeneous reaction, kg/s
k_f	mass transfer coefficient, $kg/m^2 \cdot s$
M	Molecular weight, $kg/kmol$
P	Pressure, Pa
P_i	Partial pressure of specie i , Pa
Q_{ASH}	Heat carried by ash, kJ/min
$Q_{combustion}$	Combustion heat, kJ/min
$Q_{physical}$	Heat carried by coke and gas, kJ/min
R	Gas-law constant, $8.314472 J/mol \cdot K$
R_n	Rate of reaction n , $kmol/m^3 \cdot s$
r_{dmn}	Distance between bottom of raceway and symmetry, m
S_ψ	Source term for variable ψ in Equation (1), various
T_f	Theoretical combustion temperature, K
T_g	Temperature of gas phase, K
T_m	Mean Temperature of gas and solid phase, K
V_g	Volume of gas formed in front of tuyere, Nm^3/min
$\vec{v}_j$	Physical velocity of phase j , m/s
y_{dmn}	Height of deadman at symmetry, m

Greek Symbols

Γ_ψ	Diffusion coefficient for variable ψ in Equation 1, various
ε_j	Volume fraction of phase j , -
ε_t	Turbulence dissipation rate, m^2/s^3

η Effectiveness factor of heterogeneous reaction, -
 μ Laminar viscosity, kg/m·s
 μ_t Turbulent viscosity, kg/m·s
 ρ_j Density of phase j , kg/m³
 $\sigma_k, \sigma_\varepsilon$ Turbulence model constants, -
 ψ General dependent variable in Equation 1, various
 ω_i Volume fraction of specie i in gas phase, -

Subscripts

g Gas
s Solid

Abbreviations

NG natural gas
COG coke oven gas

1 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. Kuwabara [6] and He [7] developed a one-dimensional model of blast furnace raceway to investigate the combustion behavior around raceway and the effect of the pulverized coal injection on the distribution of gas phase species and temperature. However, the raceway shape and size were ignored in the one-dimensional model, thus the simulation results were not

sufficient to be applied in production practice. Through assumption of raceway shape and size, a two-dimensional model of blast furnace raceway was applied to analyze the optimal operation conditions, such as gas flow rate, oxygen enrichment percentage and pulverized coal injection, to improve the melting efficiency [8–10]. In addition, Shen *et al.* [11, 12] further established a three-dimensional model of blast furnace raceway to provide a strong theoretical support for the pulverized coal injection.

Although lots of studies on the raceway of blast furnace have been undertaken, 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. Thus, the shape of raceway in the melter gasifier is completely different from that in the blast furnace. And, the raceway depth of melter gasifier is only about 0.7 m, which is significantly lower 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. Therefore, although there are many assumptions of the raceway shape, which is close to the actual production, in the simulation of blast furnace, they could not be applied to the raceway shape in the melter gasifier. 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 a more realistic 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.

Table 1: Variables considered in Equation 1

Phase	Equation	ψ	Γ_ψ	S_ψ
Gas	Continuity	1	0	$M_C \sum_{n=1}^3 R_n$
	Momentum	$\vec{v}_g$	0	$\varepsilon_g(-\nabla P + \rho_g \vec{g}) + \vec{F}_{gs}$
	Energy	H_g	$\lambda_g/C_{p,g}$	$-h_{gs}A_s(T_g - T_s) + M_C \cdot \sum_{n=1}^3 (R_n \cdot \Delta H_n)$
	CO	$Y_{CO,g}$	$\rho_g D_{CO}$	$M_{CO}(2R_2 + R_3 - R_4 + R_6)$
	CO ₂	$Y_{CO_2,g}$	$\rho_g D_{CO_2}$	$M_{CO_2}(R_1 - R_2 + R_4)$
	H ₂	$Y_{H_2,g}$	$\rho_g D_{H_2}$	$M_{H_2}(R_3 - R_5 + 2R_6)$
	H ₂ O	$Y_{H_2O,g}$	$\rho_g D_{H_2O}$	$M_{H_2O}(-R_3 + R_5)$
	O ₂	$Y_{O_2,g}$	$\rho_g D_{O_2}$	$M_{O_2}(-R_1 - 0.5R_4 - 0.5R_5 - 0.5R_6)$
	CH ₄	$Y_{CH_4,g}$	$\rho_g D_{CH_4}$	$-M_{CH_4} \cdot R_6$
Solid	Continuity	1	0	$-M_C \sum_{n=1}^3 R_n$
	Momentum	$\vec{v}_s$	0	$\varepsilon_s(-\nabla P + \rho_s \vec{g}) - \vec{F}_{gs}$
	Energy	H_s	$\lambda_s/C_{p,s}$	$h_{gs}A_s(T_g - T_s) - M_C \cdot \sum_{n=1}^3 (R_n \cdot \Delta H_n) + Source_{coke}$
	Coke	$Y_{C,s}$	$\rho_s D_C$	$-M_C \sum_{n=1}^3 R_n$

2 Model Formulation

2.1 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, closed by the standard $k-\varepsilon$ turbulence model. In addition, the density of gas phase is solved by the ideal gas law. 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]. Turbulent kinetic energy and turbulent dissipation rate are given by Equation (2) and (3).

$$\nabla \cdot (\varepsilon_j \rho_j \psi \vec{v}_j) = \nabla \cdot (\varepsilon_j \Gamma_\psi \nabla(\psi)) + S_\psi \quad (1)$$

Wherein the effective diffusive transfer coefficient (Γ_ψ) and the source (S_ψ) change with the different variables (ψ), as summarized in Table 1.

$$\nabla \cdot (\rho \vec{v} k - (\mu + \frac{\mu_t}{\sigma_k}) \nabla k) = G_k - \rho \varepsilon_t \quad (2)$$

$$\nabla \cdot (\rho \vec{v} \varepsilon_t - (\mu + \frac{\mu_t}{\sigma_\varepsilon}) \nabla \varepsilon_t) = \frac{\varepsilon_t}{k} (C_1 G_k - C_2 \rho \varepsilon_t) \quad (3)$$

In the actual smelting process of melter gasifier, various complicated phenomena, such as the direct reduc-

tion 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 $0.8T_g$ [16]. However, in order to take into account the above complex phenomena, a heat sink, which is described by Equation (4), is used in this model [12].

$$Source_{coke} = -h_g A (T_g - T_0) \quad (4)$$

$$T_0 = \max(0.75 T_g, 1773) \quad (5)$$

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 2. The heterogeneous reactions, including coke combustion, coke solution loss and water gas reaction, are calculated based on the heterogeneous reaction rate model [6, 8]. Their reaction rate constants (k_c) are summarized in Table 3. The finite reaction rate model [17] 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

Table 2: Chemical reactions considered in this work

n	Chemical reactions	Reaction rates expression
1	$C + O_2 \rightarrow CO_2$	$R_n = \frac{\rho_g \omega_i}{M_i} \cdot \frac{A_s}{1/k_f + 1/(\eta k_c)}$
2	$C + CO_2 \rightarrow 2CO$	
3	$C + H_2O \rightarrow CO + H_2$	
4	$CO + 1/2 O_2 \rightarrow CO_2$	$R_4 = 1.3 \times 10^{11} P_{CO} P_{O_2}^{1/2} P_{H_2O}^{1/2} \exp(-15100/T_g)$
5	$H_2 + 1/2 O_2 \rightarrow H_2O$	$R_5 = 9.87 \times 10^8 P_{H_2} P_{O_2} \exp(-3.1 \times 10^7/RT_g)$
6	$CH_4 + 1/2 O_2 \rightarrow CO + 2H_2$	$R_6 = 2.17 \times 10^{12} P_{CH_4} P_{O_2}^{1/2} \exp(-53670/RT_g)$

Table 3: Rate constant of heterogeneous reactions

n	k_c (kg/s)
1	$7260 \exp(-18000/T_m) RT_g$
2	$8.31 \times 10^9 (\rho_{coke}/A) \exp(-30200/T_m)$
3	$13.4 (\rho_{coke}/A) \exp(-17300/T_m)$

Table 4: Operating parameters of melter gasifier considered [20–23]

Parameters	Value
Melting rate	150 t/h
Fuel ratio	1062 kg/t
Plant pressure	360 kPa
Tuyere O_2 Consumption	55665 Nm^3/h
Tuyere O_2 Temperature	300 K

above, are not considered. According to the above simplified method, ignoring these reactions has little effect on the characteristics around the raceway.

2.2 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 (6) [18]. 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 [19].

Figure 1: Schematic diagram and boundary conditions of model

The diameter of tuyere is 0.03 m [20]. The typical plant operating parameters of melter gasifier, as listed in Table 4, are used as the boundary conditions [20–23]. 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].

$$\frac{y}{y_{dmn}} = 1 - 2 \left(\frac{r}{r_{dmn}} \right)^2 + \left(\frac{r}{r_{dmn}} \right)^4 \quad (6)$$

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 to the difference of additional gas injection, the gas considered in this model includes O_2 , CO , CO_2 , H_2 , H_2O , CH_4 and N_2 in the most complicated situation. (3) The solid burden only includes coke (or char formed by lump coal), with the assumption that it con-

Table 5: Comparison between highest gas temperature inside raceway from the simulated result and traditional theoretical combustion temperature

Traditional theoretical combustion temperature	Highest gas temperature	Absolute error	Relative error
3966 K	3543 K	423 K	10.7%

Figure 2: Gas phase velocity vector around raceway

sists of graphite and amorphous carbon, so its effective formation enthalpy is -1.2×10^7 J/kmol [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 [24].

The numerical technique is based on a two-dimensional, finite volume model. The total number of cells is 5513, and each cell represents a control volume. The differential equations are integrated directly in the control volume of the computational domain. The SIMPLE method for the relationship between velocity and pressure corrections and the first order upwind scheme for discretizing convection terms are applied in this model. The simulation is considered to have converged when the residual for each variable is less than 5×10^{-5} .

Figure 3: Gas phase temperature distribution around raceway

3 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 (7). 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 5.

$$T_f = (Q_{\text{combustion}} + Q_{\text{physical}} - Q_{\text{ASH}}) / (V_g \cdot c_g) \quad (7)$$

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.

Figure 4: Volume fraction distributions of gas species around raceway

Figure 5: Radial distribution of gas temperature and species along tuyere level

4 Results and Discussion

4.1 General Features

The gas phase velocity vector around raceway is shown in Figure 2. It could be found that the gas stream forms a high-speed jet, which gradually expands in the radial and axial direction, after exiting tuyere. In addition, the gas velocity could exceed 150 m/s. Under the combined effects of high speed and temperature, which will be discussed below, the tuyere thermal damage, such as the chambering in the front of tuyere, could easily occur. It is noted that a small scale of gas flow circulation is observed in front of tuyere, as shown in the circle of Figure 2. It results in a more serious thermal damage to the tuyere. Then the gas velocity decreases rapidly to a value of about 7 m/s around the raceway boundary as a result of the enlarged space and the flow resistance force. Furthermore, considering the higher void fraction of moving bed compared with the deadman, most of gas flows into the moving bed rather than the dead-

man, which leads to the higher velocity of gas in the moving bed.

The gas phase temperature distribution around raceway is described in Figure 3. Due to the coke combustion, the gas temperature around the melter gasifier raceway, reaches 3500 K and above, which is obviously higher than that of the blast furnace raceway (only 2600 K [12]). Therefore, as discussed above, the probability of thermal damage of tuyere is very high. In addition, along with the ascending gas flow, the gas phase temperature in the moving bed and the deadman gradually decreases as a result of the heat transfer between the gas and solid phases.

The volume fraction distributions of gas species (O_2 , CO and CO_2) around raceway are shown in Figure 4. Generally speaking, as the gas ascends, the O_2 concentration decreases gradually, while the CO concentration increases rapidly, and the CO_2 concentration first increases and then decreases. After reaching the raceway boundary, the volume fraction of O_2 , CO and CO_2 is about 10%, 75% and 15% respectively. Outside the raceway, the residual O_2 is consumed rapidly, due to participation in the combustion reaction. In addition, under the effect of coke solution loss, CO_2 is completely converted into CO. Therefore, in the actual production, the volume of chemical raceway based on the CO_2 concentration is larger than that of physical raceway based on the void fraction.

Three stages could be observed in the radial distributions of the gas temperature and species along the tuyere level as shown in Figure 5. 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_2 is nearly 0. In the stage 2, the increasing gas temperature improves the chemical reaction kinetics condition, the coke com-

Table 6: Chemical composition of NG and COG (vol.%)

	CH ₄	CO ₂	N ₂	H ₂	CO
NG	97	2	1		
COG	28	2	5	58	7

bustion gradually plays a leading role, the O₂ concentration decreases sharply, while the CO₂ 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 CO₂ concentration. In the stage 3, with the decreasing O₂ concentration, the coke solution loss gradually becomes dominant. Thus CO₂ concentration decreases, while the CO concentration increases, and the heat amount of gas 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.

4.2 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 N₂, 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 6. 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.

4.2.1 Gas Temperature

The effect of volume fraction of additional gas injection on the highest gas temperature in the raceway is shown in Figure 6. The volume fraction of N₂, 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 speak-

Figure 6: Effect of volume fraction of additional gas injection on highest gas temperature in raceway

ing, 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 NG 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 N₂ and COG, could not affect the normal smelting production of melter gasifier.

The reduction of gas temperature in the raceway could be analyzed from the following aspects. Firstly, for additional N₂ injection, although tuyere oxygen flow rate is constant to fix the coke combustion heat release, the additional N₂ injection increases the gas flow in the raceway, which results in decreased gas temperature in the raceway. Secondly, for additional NG injection, the combustion rate of CH₄ is faster than that of coke, while the combustion heat release of CH₄ is less than that of coke. Thus, in the case of the fixed oxygen flow rate, CH₄ robs O₂ which would otherwise combust with coke. Therefore, the higher concentration of CH₄ leads to decreased total combustion heat release. In addition, the gas temperature in the raceway further decreases, resulting from the increased gas flow rate. Thirdly, for additional COG injection, although the combustion of the main composition H₂ with O₂ would release a significant amount of heat, the water gas reaction occurs between coke and H₂O, the H₂ combustion product. Therefore, H₂ plays a role as coke combustion catalyzer and has almost no effect of total combustion heat release. However, as mentioned above, the combustion heat release of CH₄ in COG is less than that of coke, which decreases the total combustion heat release in the raceway. In addition, the increasing gas flow rate in the raceway fur-

Figure 7: Volume fraction distributions of gas species around raceway for additional N_2 injection with a concentration of 8%

ther reduces the highest gas temperature in the raceway, resulting from an accelerating heat transfer from the gas to the coke bed and a decrease in the heat amount of gas per unit volume.

4.2.2 Gas Species

In order to clearly describe the volume fraction of minor components, the volume fraction distributions of gas species around raceway for the additional gas injection with a concentration of 8% are selected and summarized in Figure 7, Figure 8 and Figure 9. The volume fraction of gas species for the additional gas injection with other concentrations are similar, so they will not be discussed below.

Generally speaking, the variation trend of volume fraction of O_2 , CO and CO_2 in the case of additional gas injection is similar with that in the case of no additional gas injection, but the volume fraction gradient of the former is relatively small. This is due to the fact that the decreasing O_2 concentration slows down the combustion reaction rate. Other special characteristics for different additional gas injection are analyzed below. For additional N_2 injection with a concentration of 8% as shown in Figure 7, with the movement of gas, the volume fraction of N_2 gradually decreases, on account of the dilution by a large amount of CO generated from the coke combustion. For additional NG injection with a concentration of 8% as shown in Figure 8, as the gas ascends, the volume fraction of H_2 increases and that of H_2O first increases and then decreases. This phenomenon mainly depends on the relative rate between wa-

Figure 8: Volume fraction distributions of gas species around raceway for additional NG injection with a concentration of 8%

ter gas reaction and H₂ combustion. In addition, the volume fraction of CH₄ obviously decreases as a result from the fast combustion reaction rate. For additional COG injection with a concentration of 8% as shown in Figure 9, the volume fraction of H₂ first decreases and then increases. This is due to the fact that the rapid H₂ combustion occurs

in front of tuyere to result in decreased volume fraction of H₂, then the water gas reaction becomes gradually dominant to increase the volume fraction of H₂.

Based on the above analysis, the additional gas injection, including N₂, NG and COG, can effectively decrease the gas temperature in the raceway to reduce the tuyere

Figure 9: Volume fraction distributions of gas species around raceway for additional COG injection with a concentration of 8%

thermal damage probability. In addition, the rising blast kinetic energy, caused by increased gas flow in the raceway, can obviously improve the center gas flow to optimize the mass and energy transfer conditions in the center zone of melter gasifier, and uniformize the hearth temperature dis-

tribution, which contributes to improved hot metal desulfurization.

Figure 10: Schematic diagram of chambering in the front of tuyere: (a) before dissecting, (b) after dissecting

4.3 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 [20]. The schematic diagram of the chambering in the front of tuyere is shown in Figure 10. 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 N_2 , 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. On the other hand, the nitride may be formed on the surface of tuyere under the condition of the high gas temperature, and it could act as a thermal insulating protective film [25]. The production practices of India Jindal [26] and China Baosteel [20] show that when the volume fraction of additional N_2 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 N_2 . 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 N_2 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.

5 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 3500 K. In addition to the above factors, a small scale of gas flow circulation in front of tuyere further deteriorates the tuyere thermal damage. Under the combined effect of the coke combustion and the coke solution loss, the volume fraction of CO gradually increases, while that of CO_2 first increases and then decreases from the tuyere to the raceway boundary. After exiting the raceway, CO_2 is completely converted into CO. Therefore, the volume of chemical raceway based on the CO_2 concentration is larger than that of physical raceway based on the void fraction. 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 N_2 , 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.

Acknowledgement: The authors would like to thank the financial support from the National Natural Science Foundation of China (No. 51704025). The authors are thankful for linguistic corrections from Mr. Siming Chen in this work.

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