NUMERICAL SIMULATION OF TEMPERATURE DISTRIBUTION AROUND RACEWAY ZONE IN COREX MELTER GASIFIER[1]

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Abstract

The raceway plays an important role in the mass and heat transportation inside the Corex melter gasifier (MG). Due to the fact that pure oxygen instead of air is injected into MG, it is of great importance to study the raceway phenomenon of MG and few works related to the subject have been reported before. Present work investigated gas velocity, species and temperature distribution behaviors in both raceway and coke bed regions by introducing a two-dimensional mathematical model at steady state. The influences of production rate and gas composition on above behaviors were further analyzed. The results show that gas velocity rapidly decreases to 8 m/s and gas species change significantly inside raceway, meanwhile the highest temperature of reducing gas reaches as high as 3742 K in front of tuyere under the production rate of 150 t/h. The increasing production rate from 150 t/h to 180 t/h reduces the highest temperature level by 20 K, and the increasing nitrogen mole concentration by 1% under the fixed oxygen flow rate reduces the highest temperature level by about 22 K, while the location of the highest temperature gas extends towards the interior of MG under the above conditions. Based on the above results, it can be concluded that in order to protect tuyere from thermal damage, the production rate and nitrogen concentration should be increased to shift the location of the highest temperature gas away from tuyere.

Key words: Corex; Melter gasifier; Mathematical model; Raceway.

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1 INTRODUCTION

Raceway plays an important role in ensuring stable operation of Corex MG. In the raceway, many complex phenomena occur, such as the generation of the high temperature reducing gas and combustion of coke. Besides, in comparison with blast furnace, pure oxygen instead of air is injected into MG. Given the above reasons, it is of great importance to study the raceway phenomenon, especially the temperature distribution, to improve the temperature state of MG. However, due to the enclosed process inside the furnace and the limitations of measuring instruments, it is difficult to study raceway phenomenon directly. Numerical simulation provides an effective way to fully understand the characteristics of temperature distribution in the raceway. Sarkar, Gupta and Kitamura[1] predicted raceway shape and size which affected the heat transfer around the raceway by using a continuum approach. Kuwabara, Hsieh and Mughi[2] developed a one-dimensional model to simulate the coke combustion in the raceway. He, Kuwabara and Muchi[3] discussed the effects of Pulverized Coal Injection (PCI) on the distribution of process variables in the combustion zone by introducing a one-dimensional model. Many attempts of two-dimensional modeling of combustion had also been reported.[4-6] These models employed numerous assumptions and some important operational features were not included. Three-dimensional models with improved simulation effects were developed by Shen et al.[7,8] and Gu et al.[9] These models were used as the guidelines to improve the PCI facilities and operations. Lots of studies on raceway have been undertaken in the blast furnace, but similar works on the MG are rarely reported, except that Pal and Lahiri[10] analyzed the effect of tuyere blocking on MG performance by developing a three-dimensional model.

Based on a two-dimensional mathematical model, the raceway phenomena in Corex MG were simulated in terms of its characteristics, such as gas velocity, species and temperature distribution behaviors in this work. In addition, the influences of production rate and gas composition on temperature distribution were also investigated.

2 MODEL FORMULATION

2.1 Assumptions

In the present work, a two-dimensional mathematical model of coke combustion in front of MG tuyere at steady state is developed with the following assumptions.

- Powder and liquid flows in the moving bed and deadman are ignored;
- the volume fraction of gas in different regions is set as constant;
- raceway shape is assumed. In the raceway, combustion of coke creates space, the coke moves down to fills this up;
- the coke flow velocity is fixed. The residence time of coke inside the deadman is 24 times more than that in the moving bed.[11,12]

2.2 Chemical Reactions

Only the reactions of coke combustion and carbon solution loss are taken into account in this model. The Field model[8] is applied to obtain the chemical reaction rate. The chemical reactions and reaction rate are listed in Table 1.

Table 1. Chemical reactions and chemical reaction rate

Chemical Reactions	Chemical Reaction rate
$C + 1/2O_2 \rightarrow CO$	$\frac{dm_{coke}}{dt} = (k_d^{-1} + k_c^{-1})^{-1} \cdot [i] \cdot 4\pi r_{coke}^2 \frac{P}{P_A}$
$C + O_2 \rightarrow CO_2$	$k_d = \frac{D_{ref}}{r_{coke}} (\frac{T_{coke} + T_g}{2T_{ref}}) \frac{P_A}{P}$
$C + CO_2 \rightarrow 2CO$	$k_c = A_c \exp(-\frac{T_c}{T_{coke}})$

2.3 Simulation Conditions

The model geometry and boundary conditions for numerical simulation are shown in Figure 1. The whole simulation region is divided into three zones according to the void fraction. The void fraction of raceway is assumed to change linearly from 1.0 to 0.5, and that of moving bed and deadman are fixed as 0.5 and 0.15, respectively. The raceway is designed as the shape of “balloon” with the diameter of 0.7 m, and deadman shape is calculated based on Eq. (1).[13] Simulations are carried out under the operating conditions listed in Table 2. Pure oxygen is injected into MG. The coke temperature is simply assumed as Max (0.8·T_g, 2073 K).

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

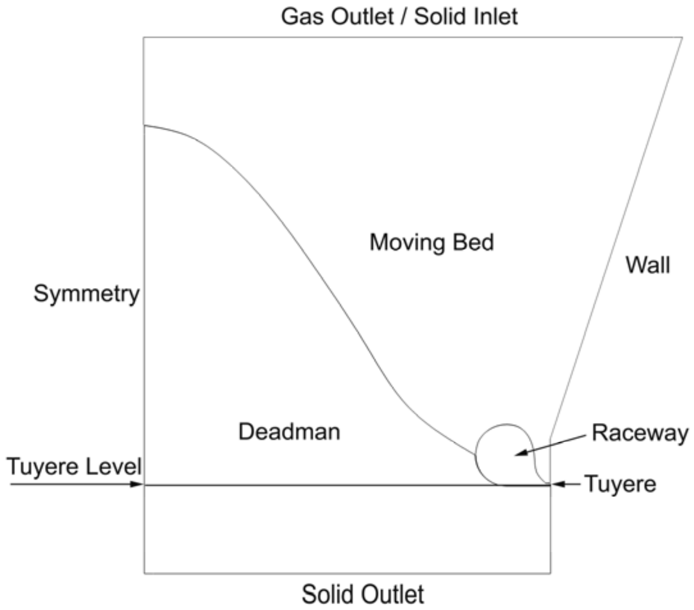

Figure 1. Geometry and boundary conditions of model.

Table 2. Operating conditions

Operating Conditions	Value
Production rate	150 tHM/h
Tuyere O_2 Consumption	55800 Nm^3/h
Coke Consumption	210 kg/tHM
Plant Pressure	360 kPa

3 RESULTS AND DISCUSSION

3.1 Flow Field, Temperature and Gas Species

Gas velocity distribution around raceway is shown in Figure 2. It could be concluded that gas velocity rapidly decreases from 160 m/s to 8 m/s after reaching the raceway boundary. In the moving bed, gas velocity gradually decreases along the vertical direction. And the velocity of gas is extremely low inside the deadman.

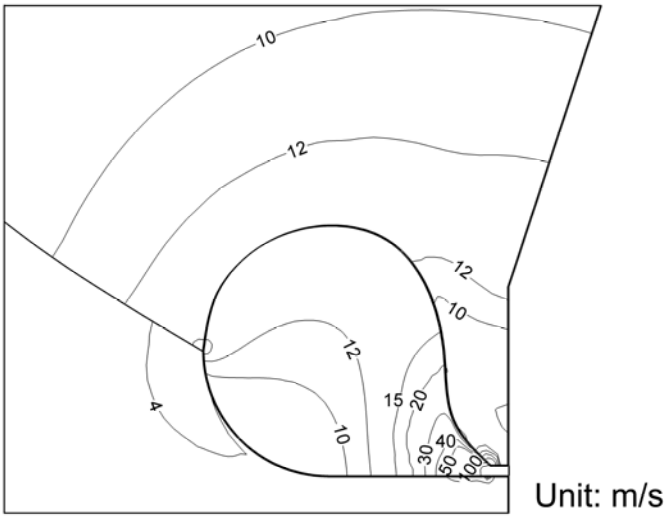

Figure 2. Gas velocity distribution around raceway.

Figure 3 displays the calculated mole fraction of CO, CO_2, O_2 in the gas phase. As the gas ascends after leaving the tuyere, O_2 concentration decreases sharply while CO concentration increases rapidly, and CO_2 concentration increases at first and then decreases. After reaching the raceway boundary, mole fraction of CO, CO_2 and O_2 are about 0.80, 0.15 and 0.05 respectively. In the moving bed, CO concentration is almost 1. CO_2 or O_2 concentration is quite low in the moving bed, even lower in the deadman. The results show that the reaction of coke combustion plays an important role at first, and then the reaction rate of carbon solution loss gradually increases with the growth of CO_2 concentration in the raceway.

Gas temperature contours around raceway is shown in Figure 4. The gas temperature reaches as high as 3,742 K in front of tuyere. Due to the heat exchange with the burden and the heat release of chemical reaction, gas temperature difference is very large. In the moving bed and deadman, the gas temperature decreases to about 2,100 K when heating the burden.

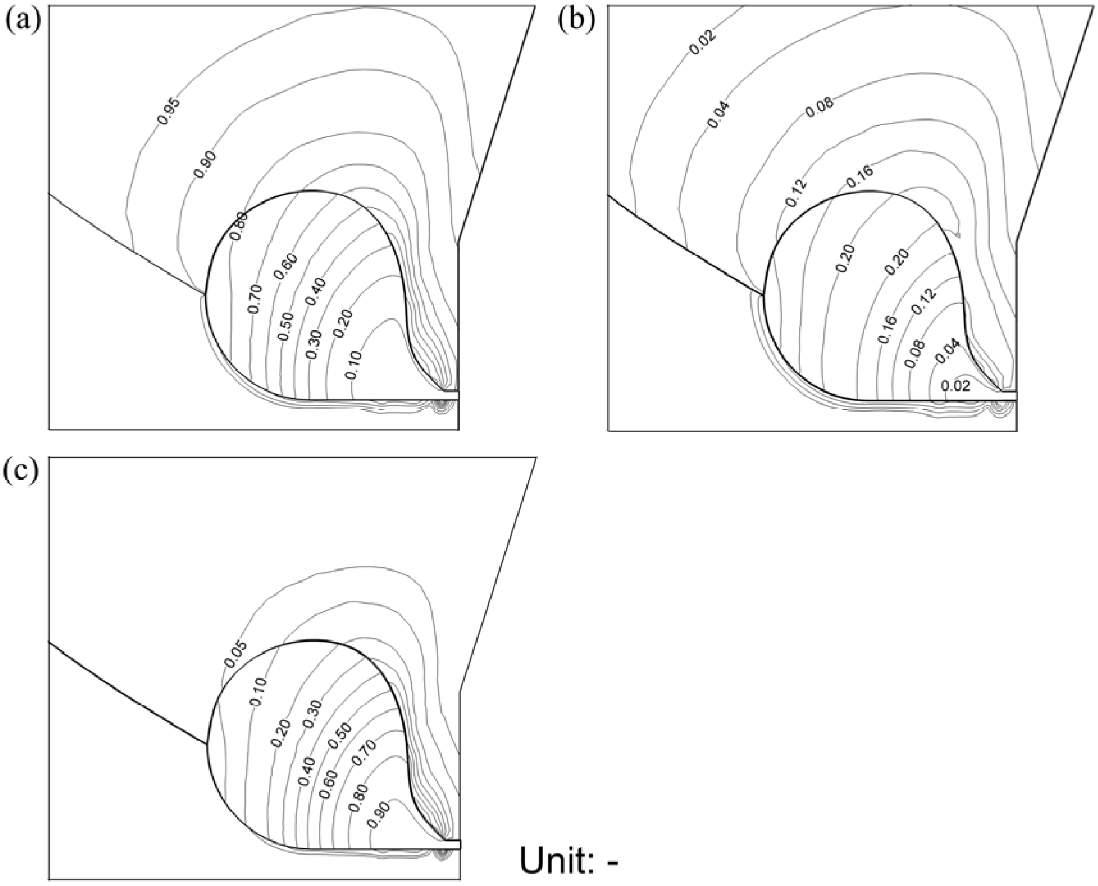

Figure 3. Mole fraction of (a) CO, (b) CO_2, (c) O_2 around raceway.

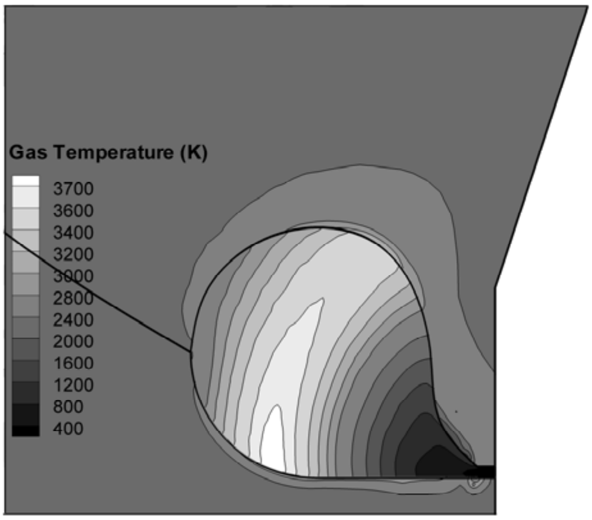

Figure 4. Gas temperature contours around raceway.

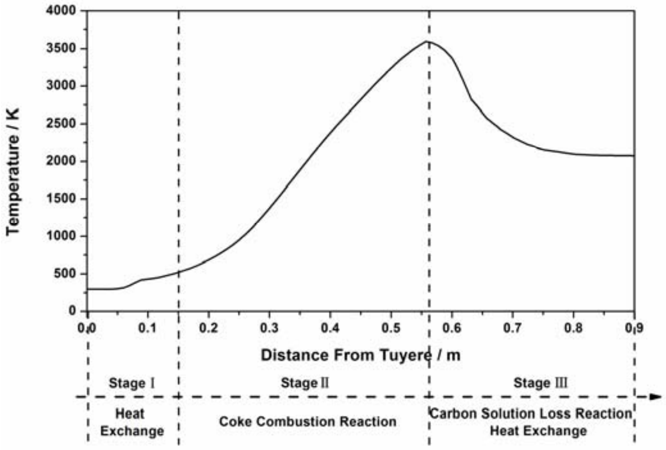

Figure 5. Distribution of gas temperature at the tuyere level.

Distribution of gas temperature at the tuyere level (referred to Figure 1) can be divided into three stages as shown in Figure 5. In Stage 1, the gas is heated up before 0.15 m, with minor change in gas temperature. In Stage 2, due to the heat release of coke combustion reaction, the gas temperature increases rapidly and reaches the max value. In Stage 3, beyond the boundaries of raceway, the gas temperature gradually decreases as a result of substantial heat absorption by carbon solution loss reaction and heat exchange with the burden.

3.2 Effect of Production Rate

Tuyere oxygen consumption has an influence on coke consumption in the raceway, which affects the production rate of hot metal. In order to investigate the influence of production rate on gas temperature distribution in the raceway, it is assumed that the gas inlet velocity as 149 m/s, 160 m/s, 171 m/s, 182 m/s and 192 m/s, with a corresponding production rate of 140 t/h, 150 t/h, 160 t/h, 170 t/h and 180 t/h respectively. The results are shown in Figure 6 and Figure 7.

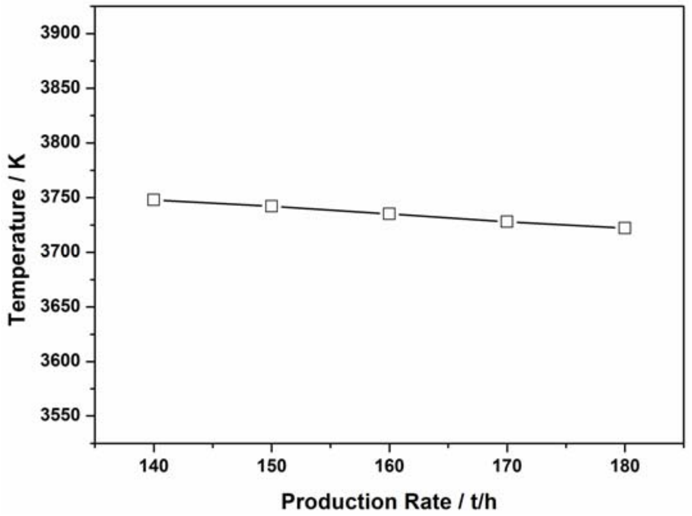

Figure 6. Influence of production rate on the highest temperature of gas in the raceway.

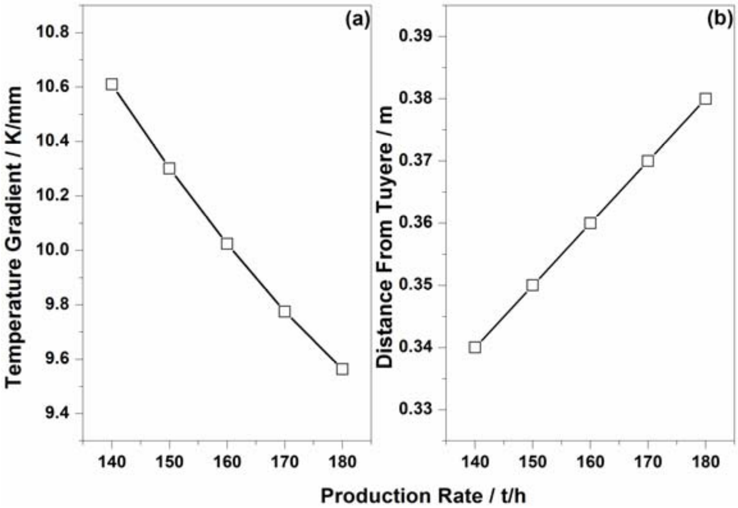

Figure 7. Influence of production rate on (a) the highest temperature gradient and (b) the location of the highest temperature gradient at the tuyere level.

As can be seen from Figure 6, the increasing production rate exerts little influence on the highest gas temperature in the raceway. The production rate increases from 150 t/h (actual production) to 180 t/h (design production), with a decrease of merely 20 K in the highest gas temperature. Figure 7 shows that the highest temperature gradient gradually decreases while the location of the highest temperature gradient extends towards the interior of MG along with the increasing production rate at the tuyere level.

The highest temperature gradient represents not only the growth of gas temperature, but also gas radiant heat transfer ability. It can be concluded that the production rate should be increased in order to protect tuyeres from thermal damage.

3.3 Effect of Gas Composition

In the actual production, additional nitrogen should be injected into MG along with pure oxygen for enhancing the blast energy. In order to investigate the influence of N_2 concentration on gas temperature distribution in the raceway, five N_2 concentrations (0, 2.5%, 5%, 7.5% and 10%) are selected. The results are shown in Figure 8 and Figure 9.

Figure 8 shows that the increasing N_2 concentration significantly decreases the highest temperature of gas in the raceway. The N_2 concentration increases by 2.5% under the fixed oxygen flow rate in the gas mixture, with a decrease of about 54 K in highest temperature of gas. Figure 9 shows that the highest temperature gradient gradually decreases while the location of the highest temperature gradient extends towards the interior of MG along with the increasing N_2 concentration at the tuyere level.

Compared with the production rate, the N_2 concentration has much more influence on the gas temperature field in the raceway. Furthermore, increasing N_2 concentration appropriately is an effective way to protect tuyere from thermal damage and improve the temperature state of MG in the actual production.

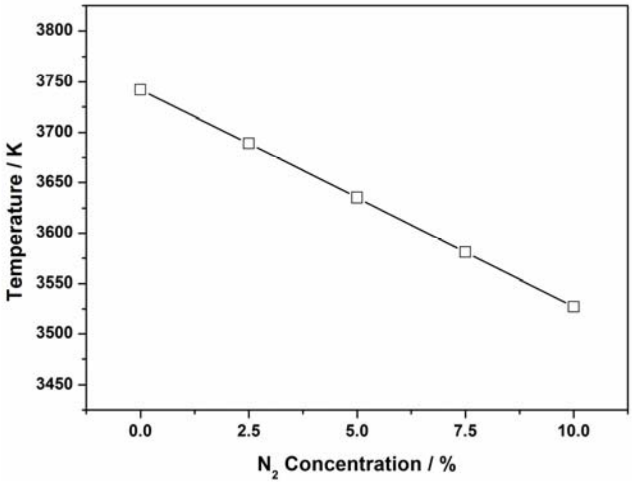

Figure 8. Influence of N_2 concentration on the highest temperature of gas in the raveway.

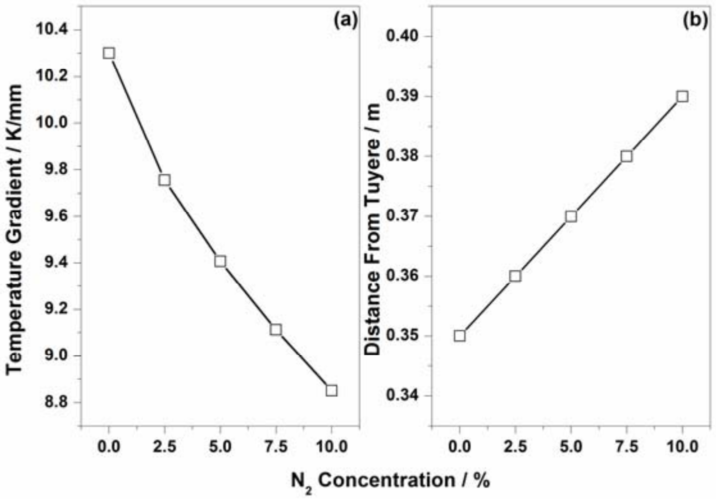

Figure 9. Influence of N_2 concentration on (a) the highest temperature gradient and (b) the location of the highest temperature gradient at the tuyere level.

4 CONCLUSIONS

A two-dimensional mathematical model at steady state is developed to calculate gas velocity, species and temperature distribution behaviors in the raceway. The conclusions are as follows:

- Gas velocity rapidly decreases to 8 m/s after reaching the raceway boundary and CO concentration increases to 0.8 rapidly inside raceway, meanwhile the gas temperature reaches as high as 3,742 K in front of tuyere under the production rate of 150 t/h;
- the increase of the production rate or the N_2 concentration reduces the highest temperature level in the raceway. The highest temperature gradient decreases while the location of the highest temperature gradient extends towards the interior of MG along with the increase of production rate or N_2 concentration at the tuyere level;
- in the actual production, the production rate and N_2 concentration should be appropriately increased to improve the temperature state of MG in order to protect tuyeres from thermal damage.

Acknowledgements

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Nomenclature

A_c : pre-exponential factors, kg/m^2·s
D_{ref} : dynamic diffusivity, 1.8×10-5 kg/m·s
k_c : oxidation rate of reactions, kg/m^2·s
k_d : diffusion rate of reactions, kg/m^2·s
P : local pressure, kPa
P_A : atmospheric pressure. kPa
r : radius, m
T : temperature, K
T_c : activation energy, K
T_{ref} : reference temperature, K
y : axial spatial coordinate, m

Subscripts
coke: coke
dmn: deadman
g: gas

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