Numerical Analysis on the Performance of COREX CGD Shaft Furnace with Top Gas Recycling

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A three-dimensional steady state mathematical model, considering the chemical reactions and the transfers of momentum, heat and mass between the gas and solid phases, is developed to investigate the performance of COREX central-gas-distribution (CGD) shaft furnace with top gas recycling (TGR). The model is validated first by data from practical measurement and then is used to study the performance of CGD shaft furnace with TGR. The results reveal that, compared with the process of 15% CGD gas input without TGR, the TGR can reduce the fresh gas consumption from 1.058 Nm³/tBurden to 0.392 Nm³/tBurden. The reduction potential of top gas with TGR increases from 0.5755 to 0.6293, the utilization rate of top gas decreases from 34.18% to 28.03%, the metallization rate of solid product increases from 61.80% to 70.05%, and the standard deviation of metallization rate decreases from 0.8% to 0.4%.

KEY WORDS: COREX shaft furnace; central gas distribution (CGD); top gas recycling (TGR); gas utilization; solid metallization.

1. Introduction

With the rapid development of iron and steel industry, the issues of environment pollution and resource consumption have become prominent, which have drawn lots of concern in the world. In recent decades, in order to reduce greenhouse gas emission and energy consumption, there have been some innovative research projects, such as the Saving One Barrel of Oil per Ton (SOBOT), A New Roadmap for Transformation of Steelmaking Process in North America, the Ultra-low CO2 Steelmaking (ULCOS) in Europe and the CO2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50 (COURSE 50) in Japan. In the whole ironmaking and steelmaking process, the ironmaking process is the largest CO2 emission and energy consumption process. The efficient utilization of the gas product from ironmaking process will effectively reduce the CO2 emission and energy consumption, and thus has great significance for the sustainable development of the iron and steel industry.

Top gas recycling (TGR) technology has been considered to be an effective method to increase the utilization of carbon and hydrogen, improve the performance of ironmaking reactor, and reduce the gas consumption. Because of the long development history of blast furnace ironmaking process, various types of TGR method have been proposed, such as the methods of Ohno, HRG, Qin, Fink, Lu and the main differences between these methods are whether with CO2 removal or not, whether with preheating or not and the different injection positions. Compared with the traditional blast furnace process, COREX process is a new ironmaking process, which has been industrialized successfully. The COREX process is a two-stage process, which includes a shaft furnace and a melter gasifier. Like the lumpy zone of blast furnace, burden is charged from the top of the shaft furnace, with the burden moving down, it is reduced to DRI and discharged from the bottom of the furnace. Correspondingly, the reducing gas is introduced from the baffle slots and the gas product is discharged from the top of the furnace. Recently, for improving the central gas distribution of large-scale shaft furnace, a central gas distribution (CGD) device is proposed and installed at the bottom of the furnace. As a brand new design, the characteristics of COREX CGD shaft furnace is still unclear, especially the effect of CGD gas input on the performance of shaft furnace with top gas recycle. Therefore, it is necessary to investigate the performance of COREX CGD shaft furnace with TGR.

Because of the severe environment in an ironmaking reactor, it is impossible to directly get the comprehensive information by measurement. Therefore, mathematical methods are widely used to study the performance of COREX shaft furnace. For example, the DEM method, which describes the granular flow at the individual particle level, is considered as an effective method to investigate the fundamental phenomena of solid flow of the shaft furnace.
In the past, many investigations have been made on the solid flow in shaft furnace, including the burden descending behavior,\(^\text{16}\) the effect of bottom base shape on burden profiles and burden size distributions in upper part,\(^\text{17}\) the effects of AGD\(^\text{18}\) and CGD\(^\text{5}\) on solid flow, and the effect of screw design on the solid flow.\(^\text{19,20}\) All the DEM studies on solid flow in shaft furnace are in reduced scale due to the too heavy computation work in full scale. On the other hand, the Eulerian method, which considers both the gas and solid phases as continuous phases, is regarded as a more efficient method to study the transfer phenomena and chemical reactions between the gas and solid phases in the shaft furnace in full scale. For instance, the investigation on the characteristics of COREX shaft furnace,\(^\text{21,22}\) including the distributions of species, temperature, solid metallization rate (MR) and gas utilization rate (UR), the effects of AGD and operation parameters on the performance of shaft furnace\(^\text{23,24}\) and the study on the performance of MIDREX shaft furnace.\(^\text{25,26}\) Even though a two-dimensional model of shaft furnace with TGR is developed, the blowing of reducing gas into DRI down pipe is somewhat arbitrary.\(^\text{27}\) Recently, a model is developed to study the performance of COREX shaft furnace with CGD in our previous work,\(^\text{28}\) however, the performance of COREX CGD shaft furnace with TGR technology have not been investigated.

In this work, the development of a three-dimensional steady state mathematical model and its validation are briefly described, and emphasis is placed on using the model to evaluate the performance of COREX CGD shaft furnace with TGR in steady operation based on detailed analysis of the effects of CGD gas fraction and TGR on the reduction process in the furnace, which has been merely studied.

2. Model Description

2.1. Model Formulation

In this work, the Eulerian method is used and both the gas and solid phases are treated as continuous phases. The transfers of momentum, heat and mass in steady state between the gas and solid phases is expressed by the conservation equation of Eq. (1).

\[
\nabla \cdot (\varepsilon_p \cdot \rho_p \cdot \vec{v}_p) = \nabla \cdot (\varepsilon_s \cdot \rho_s \cdot \vec{v}_s) + S_p \quad \ldots \ldots \quad (1)
\]

In Eq. (1), the considered phase is denoted by subscript \(p, s\) and \(S\) are the diffusivity and source term respectively. All the variables are listed in Table 1.

\[
\tau_p = \varepsilon_p \cdot \mu_p \left[ \nabla \cdot \vec{v}_p + (\nabla \cdot \vec{v}_p)^T \right] - \frac{2}{3} \varepsilon_p \cdot \mu_p (\nabla \cdot \vec{v}_p) \cdot \vec{I} \quad (29)
\]

\[
\nabla \cdot \left( \frac{\varepsilon_s \cdot \rho_s \cdot \vec{v}_s}{d_s^2} \right) = \frac{150}{6} \left( \frac{\varepsilon_s - (1 - \varepsilon_s) \cdot \mu_s}{\varepsilon_s} \right) \cdot \frac{d_s}{d_s^2} \left( \vec{v}_s - \vec{v}_g \right) \quad (30,31)
\]

\[
E_p = - \frac{6 \cdot k_s \cdot e_s - e_s}{d_s^2} \cdot (2.0 + 0.6 \cdot e_{p}^{\text{Re}}) \cdot P_{\text{T,G}}^{(3)} \cdot (T_s - T_g) \quad (32)
\]

where \(\tau_p, F_g\), and \(E_p\) are stress tensor of phase \(p\), drag force and coefficient of convective heat transfer between gas and solid phases, which are important transfer coefficients in the model.

In this work, the three-interface unreacted core model is used and all the chemical reactions in the model are listed in Table 2. Based on works of Hara et al.\(^\text{33}\) and Austin et al.,\(^\text{34}\) the reaction rate of the three-interface unreacted core model is expressed by Eq. (2).

\[
R = \frac{6 \cdot e_s}{\phi_h \cdot d_s} \cdot \frac{\rho_h}{W \cdot M_H} \sum_{i=1}^{6} \alpha_{i,n} (Y_{COH} - Y_{COH}^e) \quad \ldots \ldots \quad (2)
\]

<table>
<thead>
<tr>
<th>Term</th>
<th>Reaction</th>
<th>Rate expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_1)</td>
<td>(3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2)</td>
<td>(R = \frac{6e_i}{\phi_h \cdot d_s} \cdot \frac{\rho_h}{W \cdot M_H} \sum_{i=1}^{6} \alpha_{i,n} (Y_{COH} - Y_{COH}^e))</td>
</tr>
<tr>
<td>(R_2)</td>
<td>(Fe_3O_4 + CO \rightarrow 3FeO + CO_2)</td>
<td>(R = \frac{6e_i}{\phi_h \cdot d_s} \cdot \frac{\rho_h}{W \cdot M_H} \sum_{i=1}^{6} \alpha_{i,n} (Y_{COH} - Y_{COH}^e))</td>
</tr>
<tr>
<td>(R_3)</td>
<td>(FeO + CO \rightarrow Fe + CO_2)</td>
<td>(R = \frac{6e_i}{\phi_h \cdot d_s} \cdot \frac{\rho_h}{W \cdot M_H} \sum_{i=1}^{6} \alpha_{i,n} (Y_{COH} - Y_{COH}^e))</td>
</tr>
<tr>
<td>(R_4)</td>
<td>(3Fe_2O_3 + H_2 \rightarrow 2Fe_3O_4 + H_2O)</td>
<td>(R = \frac{6e_i}{\phi_h \cdot d_s} \cdot \frac{\rho_h}{W \cdot M_H} \sum_{i=1}^{6} \alpha_{i,n} (Y_{COH} - Y_{COH}^e))</td>
</tr>
<tr>
<td>(R_5)</td>
<td>(Fe_3O_4 + H_2 \rightarrow 3FeO + H_2O)</td>
<td>(R = \frac{6e_i}{\phi_h \cdot d_s} \cdot \frac{\rho_h}{W \cdot M_H} \sum_{i=1}^{6} \alpha_{i,n} (Y_{COH} - Y_{COH}^e))</td>
</tr>
<tr>
<td>(R_6)</td>
<td>(FeO + H_2 \rightarrow Fe + H_2O)</td>
<td>(R = \frac{6e_i}{\phi_h \cdot d_s} \cdot \frac{\rho_h}{W \cdot M_H} \sum_{i=1}^{6} \alpha_{i,n} (Y_{COH} - Y_{COH}^e))</td>
</tr>
<tr>
<td>(R_7)</td>
<td>(CO + H_2O \rightarrow CO_2 + H_2)</td>
<td>(R = \frac{1000}{(101325) \cdot \varepsilon_{k'} \cdot k'} \cdot (P_{CO} \cdot P_{H_2O} - P_{CO_2} \cdot P_{H_2}) / K_{j''})</td>
</tr>
</tbody>
</table>
2.2. Boundary Conditions

The geometrical structure of the shaft furnaces without and with CGD is shown in Fig. 1. The boundary conditions of the model are based on the practical operation conditions of the COREX-3000, which are listed in Table 3. As a typical counter-flow reactor, the burden is continuously charged from the top of the furnace, with the burden moving down, it is reduced to DRI gradually by the reducing gas and then discharged by screws at the bottom of the furnace. In addition, the reducing gas is introduced from both the bustle slots and the CGD device. After reacting with the burden, the top gas are recycled from the top of the furnace after removing the CO₂ and H₂O.

In the present model, the no-slip condition is applied to the wall of the furnace. Based on the previous works, the heat transfer coefficient, temperature and thickness of the wall are set as 20 W·m⁻²·K⁻¹, 300 K and 1 m respectively. For solid phase, the density, dynamic viscosity, thermal conductivity and particle diameter are set as 2273 kg·m⁻³, 6 kg·m⁻¹·s⁻¹, 0.8 W·m⁻¹·K⁻¹, 0.0124 m respectively. Other assumptions and boundary conditions are as follows:

1. The porosity of the moving bed is 0.4.
2. The shape factor of burden is 1.
3. The species of gas and solid phases in the model are CO, CO₂, H₂, H₂O and Fe₂O₃, Fe₃O₄, FeO, Fe.
4. The chemical reactions considered in the model are R₁–R₇ as listed in Table 2.

The main numerical method in this work is the finite-volume method. The first order upwind scheme is used to discretize the conservation equations of momentum, heat and mass, and the velocity and pressure are corrected by phase coupled SIMPLE method. The numerical calculation in this model is carried out based on the platform of the commercial CFD software, ANSYS-Fluent, and the numerical simulation in this model is considered as converged when the residual of each variable is smaller than $1 \times 10^{-5}$. In addition, the grid-independence test is conducted. The grid schemes of (a) (141 969 cells), (b) (253 192 cells), (c) (479 350 cells) for case furnace without CGD and (d) (141 486 cells), (e) (252 846 cells), (f) (477 913 cells) for case furnace with CGD were respectively tested and the average value of Fe mass fraction were 59.160%, 54.375%, 54.373% and 59.714%, 55.715%, 55.711% respectively. Therefore, considering the computational cost, the grid schemes (b) and (e) were used for the subsequent calculations.

3. Results and Discussion

3.1. Model Validation

Before using the model to study the performance of the CGD shaft furnace with TGR, the model is verified by the practical production data of COREX-3000. The comparison between measured and simulated results are listed in Table 4, including the gas composition, solid MR and relative
error.

As shown in Table 4, the maximum relative error between measured and simulated results is 5.5%, which is the volume fraction of H\textsubscript{2} at the top of the furnace. The reasons for the disagreement are analyzed as follows. Firstly, with the burden moving down, the burden sticking and the change of packed bed porosity distribution may slightly lead the disagreement between measured and simulated results. Secondly, in the model, the burden profile is assumed flat, which is different from the practical condition, and it would slightly affect the gas flow distribution at the upper part of the furnace. Lastly, besides the main species considered in the model, small part of other species exist in practical condition, such as CH\textsubscript{4}, N\textsubscript{2}, C, CaO, MgO, SiO\textsubscript{2}, etc.

Generally speaking, even though some disagreements between measured and simulated results exist, the simulated results are almost consistent with the measured data, which approves the applicability of the model in predicting the performance of the CGD shaft furnace with TGR.

### 3.2. Performance of CGD Shaft Furnace with TGR

The schematic diagram, calculation flow chart of CGD shaft furnace with TGR and gas composition are shown in Fig. 2. As shown in Fig. 2, the top gas is firstly reformed by removing CO\textsubscript{2} and H\textsubscript{2}O, and then should be preheated to a certain temperature, which could adjust the mixed gas temperature to be around 1 100 K. After dust removal, the mixed reducing gas is injected into the furnace from both bustle slots and the CGD. It should be emphasized that based on previous work,\textsuperscript{28} the actual and optimal CGD gas inputs are 15% and 40% respectively. Therefore, four types of process, including 15% CGD gas input without TGR, 15%, 40% and 100% (as a limit) CGD gas input with TGR are considered in this work. In addition, the mathematical calculation does not stop until the composition of top reformed gas (TRG) is consistent with that of updated reformed gas (URG). The gas quantities and compositions at various points are also listed in Fig. 2, showing that the reducing potential of input gas with TGR (4) is much higher than that without TGR (3). The data of gas quantity show that the TGR can reduce the relative fresh gas consumption from 1 to 0.3707, corresponding to unit consumption from 1 058 Nm\textsuperscript{3}/tBurden to 392 Nm\textsuperscript{3}/tBurden. Considering that the burden metallization is improved with TGR as shown later, the fresh gas consumption for the same metallization will be further lower.

#### 3.2.1. Temperature Distribution

The temperature distributions of the gas and solid phases in four different processes are shown in Fig. 3. As a typical counter-current reactor, the cold burden is continuously charged from the top of the furnace, after reacting with the hot reducing gas, which is introduced from both the bustle slots and the CGD, it is discharged from the furnace bottom. Therefore, a strong convective heat exchange occurs between the gas and solid phases, and a great temperature gradient appears only at the top section of the furnace.

Compared with the process of 15% CGD gas input without TGR, because the concentration of CO is higher and that of H\textsubscript{2} is lower with TGR, the temperature in the furnace is a little higher due to the exothermic reduction by CO and the endothermic reduction by H\textsubscript{2}.

Comparing the processes of different CGD gas inputs with TGR, with the CGD gas input increasing from 15% to 40%, the temperature in the furnace center decreases. This may be attributed to that the net exothermic characteristic of the total reduction by CO and H\textsubscript{2} with high H\textsubscript{2} concentration. When all gas is input from the CGD, the low temperature zone in the furnace center disappears, and this can be attributed to the large amount of heat carried by the input gas.

#### 3.2.2. Distribution of Gas Composition

The distributions of gas composition (CO, CO\textsubscript{2}, H\textsubscript{2} and H\textsubscript{2}O) in mole fraction of four different processes are shown in Fig. 4. As shown in Fig. 4, in the furnace with CGD,
because the reducing gas is introduced from both the bustle slots and CGD, the high concentration regions of CO and H₂ appear near the bustle slots and the CGD. In addition, according to Eq. (2), the high temperature and high reducing gas concentration are beneficial for the reduction reactions, therefore, the concentrations of CO and H₂ decrease rapidly and that of CO₂ and H₂O increase accordingly.

Compared with the process of 15% CGD gas input without TGR, because of the TGR, the concentration of CO with TGR increases and that of H₂ decreases obviously. It should be noticed that high CO concentration is beneficial for the reduction reaction with CO, which is an exothermic reaction, and the high temperature is beneficial for the reduction reaction with H₂, which is a strong endothermic reaction. Therefore, much CO but less H₂ are recycled back to the furnace and the H₂ concentration in the furnace with TGR is lower than that of the furnace without TGR.

3.2.3. Distribution of Reduction Potential

Reduction potential, which is defined by Eq. (3), is an important index to evaluate the reducing ability of reducing gas, hence, it is of importance to investigate the reduction potential distribution of reducing gas in the furnace. The reduction potential distributions in four different processes are shown in Fig. 5. As shown in Fig. 5, in the furnace with CGD, like the reducing gas distributions, the high reduction potential mainly distributes near both the bustle slots and CGD. Compared with the process of 15% CGD gas input without TGR, because of the TGR, the reduction potential of input gas increases greatly from 0.8744 to 0.9535 as shown in Fig. 6. Therefore, the reduction potential of reducing gas in the furnace with TGR is much higher than that without TGR, and the reduction potential of top gas increases from 0.5755 to 0.6293. The increase of top gas reduction potential is smaller than that of input gas due to the increase reduction reaction at higher reduction potential. With the CGD gas input increases from 15% to 100%, the location of high reduction potential region moves gradually from the slots area to the CGD area but the reduction potential of top gas has only a very little change of decreasing from 0.6293 to 0.6279.

\[
\text{Reduction Potential} = \frac{\varphi_{\text{CO}} + \varphi_{\text{H}_2}}{\varphi_{\text{CO}} + \varphi_{\text{H}_2} + \varphi_{\text{CO}_2} + \varphi_{\text{H}_2\text{O}}} \quad \text{(3)}
\]

3.2.4. Distribution of Solid Composition

The distributions of solid composition (Fe₂O₃, Fe₃O₄, FeO and Fe) in mass fraction in four different processes are shown in Fig. 7. According to the three-interface unreacted core model, the burden is successively reduced from Fe₂O₃→Fe₃O₄→FeO→Fe. Comparing the thermodynamic and kinetic parameters of reduction reactions, which are listed in Table 2, the reactions Fe₂O₃→Fe₃O₄ are the easiest to proceed but the reactions FeO→Fe are the hardest to proceed, which need higher reducing gas concentration and temperature. Therefore, with the burden being charged from
Fig. 4. Composition distributions of gas phase in four different processes. (Online version in color.)
the top of the furnace, it is rapidly reduced from Fe$_2$O$_3$ to Fe$_3$O$_4$. With the burden moving down, the burden is successively reduced from Fe$_3$O$_4$ to FeO. However, because the reaction rate constants and chemical equilibrium constants of FeO→Fe reaction are smaller than others, only part of FeO is reduced to Fe at the bottom of the furnace.

Compared with the process of 15% CGD gas input without TGR, because of the TGR, the reduction potential of reducing gas in the furnace with TGR is higher, and thus the mass fraction of Fe at the bottom of the furnace increases from 55.71% to 64.52%, which is shown in Fig. 8. With the CGD gas input increases from 15% to 100%, the high reduction potential and high temperature regions mainly distribute near the CGD, and the distribution of the mass fraction of Fe has the same tendency, which increases from 64.52% to 65.52%.

### 3.2.5. Distribution of Gas Utilization Rate and Solid Metallization Rate

The gas utilization rate (UR) and solid metallization rate (MR), which are defined by Eqs. (4) and (5) respectively, are important indexes to evaluate the furnace running state. High gas UR and solid MR indicate that the furnace is in an efficient running state. Hence, it is of importance to investi-gate the distributions of gas UR and solid MR in the CGD furnace with TGR.

\[
\text{Gas UR} = \frac{\left(\phi\text{CO}_{\text{inlet}} - \phi\text{CO}_{\text{outlet}}\right) + \left(\phi\text{H}_2 - \phi\text{H}_2\right)}{\phi\text{CO}_{\text{inlet}} + \phi\text{H}_2_{\text{inlet}}} \quad \text{(4)}
\]

\[
\text{Solid MR} = \frac{112}{160} \cdot \frac{w_{\text{Fe}}}{w_{\text{FeO}} + \frac{168}{232} \cdot w_{\text{FeO}} + \frac{56}{72} \cdot w_{\text{FeO}} + w_{\text{Fe}}} \quad \text{(5)}
\]

The distributions of gas UR and solid MR in four different processes are shown in Fig. 9. According to Eq. (4), the gas UR is determined by the gas composition. With the reducing gas moving up, the gas UR increases gradually and reaches the maximum value at the top of the furnace. It should be noticed that the gas UR decreases due to the increase of reduction potential of input gas with TGR. Compared with the process of 15% CGD gas input without TGR, the top gas UR with TGR decreases from 34.18% to 28.03%. With the CGD gas input increases from 15% to 100%, the top gas UR increases from 28.03% to 28.11% as shown in Fig. 10.

According to Eq. (5), the solid MR is determined by the solid composition. With the burden moving down, the burden is gradually reduced from Fe$_2$O$_3$ to Fe$_3$O$_4$ to FeO to Fe and the solid MR correspondingly reaches the maximum value at the bottom of the furnace. Compared with the process of 15% CGD gas input without TGR, the reduction potential of reducing gas with TGR is higher, leading to that the reduction reactions proceed more complete and the solid MR increases from 61.80% to 70.05%. In addition, the standard deviation (STDEV) of solid MR decreases from 0.8% to 0.4%, which means that the DRI MR from the furnace with TGR is more uniform than that without TGR. When the CGD gas input increases from 15% to 40%, the solid MR increases from 70.05% to 70.45% and the STDEV of solid MR increases from 0.4% to 0.7%. However, with the CGD gas input increases further from 40% to 100%, the solid MR increases from 70.45% to 70.93% and the STDEV of solid MR increases sharply from 0.7% to 3.0%. The results reveal that the TGR could increases the solid MR obviously and a proper CGD gas input is favorable for the uniformity of DRI MR, and the recommended CGD gas input is 40%.
Fig. 7. Composition distributions of solid phase in four different processes. (Online version in color.)
4. Conclusions

(1) The TGR can decrease the fresh reducing gas consumption from 1 058 Nm$^3$/tBurden to 392 Nm$^3$/tBurden.

(2) Compared with the process of 15% CGD gas input without TGR, the reduction potential of reducing gas in the furnace with TGR increases from 0.5755 to 0.6293, the gas UR decreases from 34.18% to 28.03%, the solid MR increases from 61.80% to 70.05% and the STDEV of solid MR decreases from 0.8% to 0.4%.

(3) With the CGD gas input increases from 15% to 40%, the solid MR increases from 70.05% to 70.45% and the STDEV of solid MR increases from 0.4% to 0.7%. When the CGD gas input increases further from 40% to 100%, even though the solid MR increases from 70.45% to 70.93%, the STDEV of solid MR increases sharply from 0.7% to 3.0%. The proper CGD gas input is recommended as 40%.

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**Fig. 8.** Mass fraction of Fe in four different processes.

**Fig. 9.** Distributions of gas UR and solid MR in four different processes. (Online version in color.)

**Fig. 10.** Distributions of gas UR, solid MR and STDEV of solid MR in four different processes. (Online version in color.)
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Nomenclature

\[ C_{p,i} \]: Specific heat capacity of species \( i \) (\( J/(kg\cdot K) \))

\[ d_i \]: Particle diameter of solid phase (m)

\[ E_{gs} \]: Coefficient of convective heat transfer (W/ (m\(^2\)·K))

\[ F_p \]: Drag force between gas and solid phases (N/m\(^2\))

\[ \ddot{g} \]: Gravitational acceleration (m/s\(^2\))

\[ H_p \]: Enthalpy of phase \( p \) (J/kg)

\[ \Delta H_L \]: Enthalpy of reaction \( n \) (J/kg)

\[ K_e \]: Equilibrium constant of reaction \( n \) (–)

\[ k_c \]: Thermal conductivity of species \( i \) (W/(m·K))

\[ k_r \]: Rate constant of reaction \( n \) (–)

\[ M_i \]: Molecular weight of species \( i \) (kg/kmol)

\[ M_{fg} \]: Average molecular weight of gas phase (kg/kmol)

\[ P \]: Pressure (Pa)

\[ Pr_g \]: Prandtl number (–)

\[ R_e \]: Chemical reaction rate of reaction \( n \) (kmol/(m\(^3\)·s))

\[ Re_c \]: Relative Reynolds number based on solid particle diameter (–)

\[ S_{\phi} \]: Source term of variable \( \phi \)

\[ T_p \]: Temperature of phase \( p \) (K)

\[ \dot{\phi}_p \]: Velocity of phase \( p \) (m/s)

\[ W \]: Variable explained in Ref. 33

\[ Y_i \]: Mole fraction of species \( i \) (–)

\[ Y_{m,i} \]: Mole fraction of species \( i \) under equilibrium of reaction \( m \) (–)

Greek symbols

\[ \alpha_{m,i} \]: Variable explained in Ref. 33

\[ w_{i,\phi} \]: Mass fraction of species \( i \) in phase \( j \) (–)

\[ \xi_{\phi} \]: Volume fraction of phase \( p \) (–)

\[ \rho_{\phi} \]: Density of phase \( p \) (kg/m\(^3\))

\[ \phi \]: General dependent variable in Eq. (1)

\[ \tau_p \]: Stress tensor of phase \( p \) (Pa)

\[ \mu \]: Average value of array element

\[ \varphi \]: Gas composition in volume fraction (–)

\[ \Gamma \]: Effective diffusion coefficient (m\(^2\)/s)

Subscripts

\( g \): Gas

\( s \): Solid

Abbreviations

AGD: Areal Gas Distribution

CGD: Central Gas Distribution

DRI: Direct Reduction Iron

MR: Metallization Rate

STDEV: Standard Deviation

TGR: Top Gas Recycling

TRG: Top Reformed Gas

URG: Update Reformed Gas

UR: Utilization Rate

REFERENCES


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