1. Introduction

Alumina-rich iron ore is a widely existed polymetallic deposit in the nature, and it has a high comprehensive utilization value. Because the alumina and iron contents of alumina-rich iron ore vary from each other, there are many different measures and processes to recover iron and alumina from the various kinds of alumina-rich iron ore. In the blast furnace (BF) ironmaking process, the alumina content in the iron ore fines used in sintering making all over the world is mostly less than 2%, but 2.5–5.5% in India.1–3) As the less-slag operation is promoted in the recent blast furnace operation, the Al_2O_3 in the BF slag increases and thus would cause troubles such as increasing pressure drop in the dripping zone and increasing the gas flow resistance in the cohesive zone. The study by Sunahara4) indicates that the optimum composition of high Al_2O_3 slag is high MgO and low CaO/SiO_2. The recovering of Al_2O_3 from slag with high content of MgO is difficult due to the appearance of 20CaO·13Al_2O_3·3MgO·3SiO_2 (Q phase) in the slag,5) so the slag is used as raw material for other industrial production, such as cement production, which would bring certain resource waste of Al_2O_3.

Alumina-rich iron ore with 40% or more Al_2O_3 is first processed into Al_2O_3 and red mud by combined Bayer process or pure Bayer process,6) and then the ferric oxide and the residual Al_2O_3 in the red mud is to be recovered by other methods. Wanchao Liu7) obtained an iron recovery rate of 81.4% with direct roasting reduction process from a red mud with 27.93% Fe_2O_3 and 22.00% Al_2O_3 and the residuals with Al_2O_3 were used for building material production. Xiaobin Li8) adopted a process of reduction-sintering of a red mud with 32.52% Fe_2O_3 and 18.42% Al_2O_3 and the recovery rates of iron and alumina were 60.67% and 89.71%, respectively. Compared with these two results, the iron and alumina content of the red mud were not fully recovered, the former high iron recovery rate but low alumina recovery rate and the latter on the contrary.

Other alumina-rich iron ore with Al_2O_3 content between 5.5–40% cannot be used in BF process or Bayer process. So the smelting reduction processes which are used as economic and environmental friendly alternative ironmaking processes are considered to utilize these polymetallic resources. A two-step three-vessel smelting reduction process for processing alumina-rich iron ore is proposed in this study, and the schematic diagram is shown in Fig. 1. The pelletized iron ore with coal is firstly preheated in a pre-heating furnace and pre-reduced in a Rotary Hearth Furnace (RHF) to a pellet metallization rate (PMR) of 80%. The heat carried by exhaust gas of RHF is used to pre-heat oxygen-rich air and pellet. The metallized alumina-rich iron oxide pellet at 900°C is charged directly into the Smelting Reduction Vessel (SRV) with a thick slag bath. The final reduction and melting of pellet take place in the thick slag bath of the SRV, which can not only separate the melting and reduction zones gradiently and prevent the reoxidation of iron droplet (pure iron reduced from iron oxides) in the
slag, but also make the heat transfer more efficient from the post combustion of top gas to slag. The top gas generated by the SRV with a post combustion ratio (PCR) of 55% is reformed in the Gas Reforming Furnace (GRF) and the required heat comes from its sensible heat. The reformed gas is used in the RHF to produce heat for the reduction of the pellet.

An overall process model was established in this study and the mass and heat balance calculations were carried out to investigate the consumptions of raw material and energy of the entire process, including RHF, SRV, and GRF. The PCR in SRV and the PMR in RHF were optimized to balance the raw material consumption and heat loss. As the SRV is a complicated reactor and zoned model can get more insight into the process, a zoned static model was also established to make further exploration of the SRV operation conditions.

2. Establishment of the Models

The basic principle of the models is that, on the basis of the mass balances, the result was obtained from the coupling calculation of mass and heat consumption. The thermodynamic data used in the calculation are generally acknowledged data from literature. The chemical compositions of the alumina-rich iron ore, coal, and hot metal are listed in Tables 1, 2 and 3, respectively.

2.1. The Overall Model for the Entire Process

The overall model consists of three calculation modules including RHF calculation module, SRV calculation module and GRF calculation module which were illustrated in the flow chart in Fig. 2. The composition of the metallized pellet as an output data of RHF is used in the SRV module, the composition of exhaust gas of SRV is used in the GRF module, and the reformed gas is used in the RHF module. The Gas++ in Fig. 2 means that the mass of gas is an assignment and progressively increases in the iteration, Coal−− means that the mass of coal progressively decreases.

2.2. Chemical Composition of Alumina-Rich Iron Ore (mass%)

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass%</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFe</td>
<td>24.75</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>35.09</td>
</tr>
<tr>
<td>CaO</td>
<td>15.34</td>
</tr>
<tr>
<td>MgO</td>
<td>0.50</td>
</tr>
<tr>
<td>SiO₂</td>
<td>10.93</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>29.92</td>
</tr>
<tr>
<td>MnO</td>
<td>0.27</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.32</td>
</tr>
<tr>
<td>S</td>
<td>0.045</td>
</tr>
<tr>
<td>Rest</td>
<td>7.345</td>
</tr>
</tbody>
</table>

2.3. Chemical Composition of Coal (mass%)

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass%</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>5.00</td>
</tr>
<tr>
<td>Ash</td>
<td>8.52</td>
</tr>
<tr>
<td>Vol</td>
<td>10.71</td>
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<tr>
<td>C fix</td>
<td>84.85</td>
</tr>
<tr>
<td>C</td>
<td>84.85</td>
</tr>
<tr>
<td>H</td>
<td>3.17</td>
</tr>
<tr>
<td>O</td>
<td>1.12</td>
</tr>
<tr>
<td>N</td>
<td>1.18</td>
</tr>
<tr>
<td>S</td>
<td>0.39</td>
</tr>
<tr>
<td>Rest</td>
<td>6.40</td>
</tr>
</tbody>
</table>

2.4. Chemical Composition of Hot Metal (mass%)

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>94.72</td>
</tr>
<tr>
<td>C</td>
<td>4.00</td>
</tr>
<tr>
<td>Si</td>
<td>0.70</td>
</tr>
<tr>
<td>Mn</td>
<td>0.35</td>
</tr>
<tr>
<td>P</td>
<td>0.20</td>
</tr>
<tr>
<td>S</td>
<td>0.03</td>
</tr>
<tr>
<td>Rest</td>
<td>0</td>
</tr>
</tbody>
</table>
on the reverse, and Coal++ means that the mass of coal progressively increases in the iteration.

2.1.1. RHF Calculation Module

The RHF is used for the reduction of carbon-bearing alumina-rich iron oxide pellet, because the direct reduction of alumina-rich iron oxide pellet by gas is very difficult to reach a high reduction degree.13) The main reactions in the RHF are the reduction of iron oxide by solid carbon, post combustion of gas generated by reduction, and the gas combustion from the tuyere. As the metallization rate and residual carbon of the pellet are set, its coal consumption can be determined directly. Combining the assumption of 100% PCR of the exhaust gas and the heat balance Eq. (1), the oxygen and gas consumptions can be calculated and other mass and heat changes in the RHF can be calculated from the mass balance with iteration.

\[ \sum_{i} Q_{R-HL} + Q_{R-c_{0}} + Q_{R-c_{p}} + Q_{R-cv} = Q_{R-c_{0}} + Q_{R-c_{i}} + Q_{R-HL} \ldots \quad (1) \]

Here, in the Eq. (1), \( i \) donates the raw materials including gas, oxygen-rich air and alumina-rich pellet. \( Q_{R-HL} \) represents the sensible heat of raw material \( i \) fed into the RHF. \( Q_{R-c_{0}}, Q_{R-c_{p}}, \) and \( Q_{R-cv} \) donate the combustion heat of gas from the tuyere, gas generated by reduction and the volatiles of coal in the pellet. \( j \) donates the products of RHF including metallized pellet and exhaust gas. \( Q_{R-c_{0}}, Q_{R-c_{p}} \) represents the sensible heat of products out of RHF. \( k \) donates the reactions taking place in the RHF including the reduction of iron oxides and the decomposition of limestone. \( Q_{R-c_{0}} \) represents the reaction heat. \( Q_{R-HL} \) donates the heat loss in the RHF.

The basic operation conditions of RHF were set according to the situation of current RHFs in China, which were 300°C of pellet pre-heating temperature, 800°C of oxygen-rich air, 30% of air oxygen enrichment, 1 100°C of exhaust gas temperature, and 20% of heat loss. The temperature of gas from tuyere was determined by the follow-up process GRF due to its characteristics which will be discussed in the latter paragraph. The metallization rate of pellet is one of the most important factors in practical production, which will be investigated in different values to study the mass and heat consumption of the whole process, so as to obtain the optimum metallization rate for practical application.

\[ \sum_{i} Fe = Fe_{H} + Fe_{S} \quad \ldots \quad (2) \]

\[ \sum_{i} Al_{2}O_{3} \cdot (CaO_{i}/Al_{2}O_{3}) + \sum_{i} SiO_{2} \cdot (CaO_{i}/SiO_{2}) \quad \ldots \quad (3) \]

\[ \sum_{i} CaO = \sum_{i} S \]

In the Eqs. (2) and (3), \( i \) donates the raw materials including lime and pellet, and \( \sum_{i} Fe \) represent the mass of Fe in the raw material. \( Fe_{H} \) and \( Fe_{S} \) donate the mass of Fe in the hot metal and the slag, respectively. \( \sum_{i} Al_{2}O_{3}, \sum_{i} SiO_{2}, \sum_{i} CaO \) and \( \sum_{i} S \) represent the masses of the \( Al_{2}O_{3}, SiO_{2}, CaO \) and \( S \) in the raw material. (\( CaO_{i}/Al_{2}O_{3} \) and \( CaO_{i}/SiO_{2} \) represent two mole ratios. The first is the ratio of part of \( CaO \) and all the \( Al_{2}O_{3} \) in the raw material; the second is the ratio of the rest part of \( CaO \) and all the \( SiO_{2} \) in the raw material. These two values are taken as 1.4 and 2 respectively according to the requirement for \( Al_{2}O_{3} \) leaching.

The volume and composition of gas released from the SRV are calculated by four Eqs. (4)–(7) as the \( C \) and \( H \) balance equations, the PCR equation, and the equilibrium of water gas shift reaction. In these equations, \( i \) donates the raw materials including coal, pellet and lime, \( \sum_{c} C \) represents the mass of \( C \) in the raw materials such as fix carbon in the coal, residual carbon in the pellet, carbonates in the lime, etc. \( C_{HM} \) donates the mass of \( C \) in the hot metal, \( C_{G} \) donates the mass of \( C \) in the gas, \( \sum_{c} H \) represents the mass of \( H \) in the raw material, \( H_{G} \) donates the mass of \( H \) in the gas, and PCR donates the PCR of gas.

\[ \sum_{i} C = C_{HM} + C_{G} \quad \ldots \quad (4) \]

\[ \sum_{i} H = H_{G} \quad \ldots \quad (5) \]

\[ (CO_{2} + H_{2}O)/(CO+ H_{2} + CO_{2} + H_{2}O) = PCR \quad \ldots \quad (6) \]

\[ CO+H_{2}O=CO_{2} + H_{2} \quad \Delta G_{a}^{o} = -29490 + 26.87 T \quad J/mol \quad \ldots \quad (7) \]

The main energy incomes of the SRV are the sensible heat of pellet, combustion of Coal, post combustion of \( CO \) and \( H_{2} \), and the latent heat of slag-forming. The heat generated by post combustion goes to three directions including the sensible heat of gas, heat transferred to the slag, and the heat loss. The percentage of the heat transferred to the slag is defined as the heat transfer efficiency of post combustion and it is calculated by Eq. (8).

\[ \eta_{PC} = \frac{Heat \ transferred \ to \ the \ slag}{Heat \ generated \ by \ post \ combustion} \times 100\% \quad \ldots \quad (8) \]

The slag phase diagram is used for the calculation of slag-forming latent heat. With the composition of slag, the position of the slag in the phase diagram can be located and the component triangle around it gives the phase composition of the slag. The latent heat of slag-forming is expressed by the sum of formation heat of the three components on the triangle vertices. Figure 3 shows part of the \( CaO-SiO_{2}-Al_{2}O_{3} \) phase diagram that contains the most of BF slag and high alumina slag. The \( C, S \) and \( A \) in Fig. 3 represent \( CaO, SiO_{2} \) and \( Al_{2}O_{3} \), respectively. For the convenience of calculation, three calculation units are established for three component triangle as 1: \( CS-C_{2}S_{2}-CS-C_{3}S_{2} \), 2: \( C_{2}S-C_{2}AS-CA \), and 3: \( C_{2}S-C_{2}AS-C_{2}A_{2}-CA \), as shown in Fig. 3. Once the composition of slag is worked out, the judgment statement will lead the program into the correct unit to calculate, and the slag-forming latent heat is then obtained. The sensible heat of the slag is also calculated in the same way.

The operation conditions of the SRV are determined by the reference to the data of the current Blast Furnace. The slag temperature is set as 1 550°C, the hot metal temperature
is set as 1 500°C, and the exhaust gas temperature is set as 1 650°C. The pellet temperature is set as 900°C in the consideration of heat loss during the transfer form RHF to SRV. Pure oxygen is used as the combustion supporting gas. The PCR is investigated as a main process parameter to optimize the energy consumption of the SRV and then the optimum PCR can be obtained.

2.1.3. GRF Calculation Module
The energy income of GRF is the sensible heat of exhaust gas from SRV. Because the main gas reforming reaction, i.e. the solution loss reaction in the Eq. (9) does not proceed significantly below 900°C,14) the gas temperature out of GRF is set as 900°C and the composition of the GRF gas and the coal consumption are calculated by the judgment of equilibrium of Eq. (7) with the temperature and composition of the SRV gas, during which the coal increases progressively in the iteration till the reaction reaching its equilibria. The results agree well with the experiment results from the literature,14) then the calculation results can be used to optimize other operation parameters.

\[ \text{C} + \text{CO}_2 = 2\text{CO} \quad \Delta G^{\circ} = 123 115 - 175T \text{ J/mol} \quad (9) \]

2.2. Zoned Model of the SRV
The SRV is designed for not only the final reduction and melting of the pre-reduced pellet but also the composition adjusting of slag that can be used in the later Al$_2$O$_3$ leaching process. A schematic diagram of the SRV is shown in Fig. 4 where the three-level lance arrangement and four different reaction zones are also illustrated. The oxygen lances on the top level is inserted into the free space on top of slag (zone 1). They are designed to supply pure oxygen for the post combustion of gas and the high flow velocity will also promote the heat transfer efficiency of post combustion. Both the oxygen-coal lances are of coaxial double pipes. The lances in the middle are inserted into the upper slag (zone 2) to provide sufficient energy for the melting of pellet. The stirring action of the middle lance in the upper slag will enhance the heat convection between post combustion gas and slag and increase the heat transfer efficiency. The lances at the bottom are inserted into the lower slag (zone 3) and mainly to supply reducing agent for the reduction of the iron oxides, and oxygen will be injected if the heat transfer to the lower slag is not sufficient from the sensible heat of upper slag or the temperature of hot metal (zone 4) becomes too low.

For the SRV with three-level lances, each reaction zone has different functions and the process condition is not the same as well, so the overall static model cannot provide full-scale technical data to guide the operation of SRV. A zoned model, as schematically illustrated in Fig. 5, was established for further study of the process condition of each reaction zone.

The model consists of three modules including zone 1, the top free board space for gas post combustion; zone 2, the upper slag zone for melting; and zone 3, the lower slag zone for reducing. The calculation starts with zone 2 and gives the initial gas composition of zone 1, then the iteration begins till the heat calculation reaching its balance. The calculation of zone 3 starts with the initial data of slag and iron droplets and gives back gas composition to zone 2, then the whole system starts its iteration till all the heat calculations reaching their balances.

3. Results and Discussion
Figure 6 shows the results of the overall static model under the condition of 80% PMR, 55% PCR, and 80% heat transfer efficiency of post combustion. To produce 1 t hot metal, 3 625.54 kg alumina-rich metallized pellet is needed, along with 2 057.97 kg lime, 1 524.50 kg coal and 2 475.07 kg oxygen. Because the Fe grade of the alumina-rich iron ore is low, and the slag-adjusting requires a large amount of lime to make the composition suitable for Al$_2$O$_3$, Fig. 5. Flow chart of zoned static model of SRV.

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leaching, the coal consumption of the SRV is relatively high. About 4.1 t slag is also obtained, from which about 4.1 × 29.12% ≈ 1.2 t Al₂O₃ may be expected.

The sensible heat of the RHF exhaust gas is a valuable energy resource to recycle for the pre-heating of the pellet and air. The sensible heat of the 1 100° C, 2 630.22 kg exhaust gas is 3 262 327.96 kJ, of which 781 270.88 kJ is used for 300° C pre-heating of the 3 781.66 kg pellet, and 1 491 536.06 kJ is used for 800° C pre-heating of the 1 793.16 kg oxygen-rich air. The sensible heat can be fully used if the heat exchange efficiency of the exchanger is 70%. There is a huge amount of reformed gas from GRF with high reduction potential and temperature which is far more than the requirement of RHF, the extra gas can be used for energy storage or electricity generation in order to make full use of the energy of the process.

The slag with high alumina content produced in SRV contains 7 781 308.01 kJ sensible heat which can be efficiently recovered during the cooling process. Because the phase composition of the alumina-rich slag has special requirements for Al₂O₃ leaching, the cooling process of the slag should be slow rather than quenching by water or gas. Then the heat recovery will be more efficient. Assuming that 50% of the sensible heat can be recovered, 2 161.47 kWh will be available for electricity generation. As the raw material for alumina extraction with leaching rate of 86% (former experiment result15), about 1 t Al₂O₃ can be obtained from the slag. After Al₂O₃ leaching, the residual will be a good material for cement production.

3.1. Effect of Heat Transfer Efficiency of Post Combustion in SRV

Figure 7 shows the effect of heat transfer efficiency of post combustion on SRV coal and oxygen consumptions under the condition of 80% PMR and 55% PCR of SRV gas. The coal and oxygen consumption increase rapidly with the decrease of the heat transfer efficiency.

The mechanisms of heat transfer in the smelting reduction process with a thick slag layer in a top and bottom blown converter was studied by H. Katayama, et al.16–18) The study indicates that if the gas temperature is below 1 765° C, the heat transfer by radiation and gas convection can account for only 30% or less of the total heat transfer, but sufficient amount of carbonaceous material and moderate intensity of stirring in the slag contribute greatly to the heat transfer. The heat transfer efficiency is about 90% in their study.

For the smelting reduction process with thick slag layer for alumina-rich iron ore proposed in the present work, the oxygen lances in the free space ensure the heat transfer by radiation and gas convection, and the oxygen and coal lances in the upper slag supply coal and enhance the stirring action of the slag, and the gas generated by the reduction in the lower slag also takes a part in the stirring, so the heat transfer efficiency of the process can be improved by all these measures. The heat transfer efficiency of the post combustion in the top free space in the model is assumed to be 80% for the conservative calculation of the process and used in the following calculations.

3.2. Effect of PCR in SRV

The gas post combustion in SRV plays an important role in the materials and particularly heat balances, and it has significant influence on the coal consumption of each part of the process. Figure 8 shows the effect of gas PCR on the coal consumption of RHF, SRV and GRF. The coal consumption of SRV decreases with the increase of PCR, but the decreasing rate slows down gradually. When the PCR gets higher, more heat will be generated by the same amount of coal and supplied to the SRV, so less coal is needed for the required energy. But the 10% absolute heat loss of total output heat assumed in the model limits the coal saving. The coal consumption of the GRF decreases with the increase of PCR. This is because that high PCR reduces the SRV gas generation as shown in Fig. 9. And the SRV oxygen consumption also decreases with the increase of PCR. So, for the GRF, less gas generation and high PCR make the equilibrium condition of the gas reforming reaction different from each other. The reduction potential of the reformed gas is decreased with the increase of PCR as shown in Fig. 10.

When the metallization rate of the pellet is set as constant of 80% while the PCR changes, the coal consumption is the same for producing the same amount of metallized pellet. The total coal consumption of the process decreases with...
Heat loss exists in each part of the process including the heat loss of the furnace itself and the heat loss during the heat recovery of the RHF exhaust gas and SRV slag. The values of absolute heat loss are 20%, 10% and 10% of the total output heat of RHF, SRV and GRF, 30% of sensible heat of RHF exhaust gas, and 50% of sensible heat of SRV slag. The relative heat loss is the percentage that heat loss takes from the total output heat. The total absolute heat loss decreases with the increase of SRV PCR as shown in Fig. 11 where ce is the abbreviation of coal equivalent and 1 kg ce corresponds to 29,270 kJ. Figure 11 also indicates that the relative heat loss increases with the increase of PCR. As a result, the absolute heat loss is reduced, but the heat utilization ratio is also reduced.

In conclusion, the recommended PCR is 55% and it is used in the following calculations. The relative and the absolute heat loss are at moderate levels. With further increase of PCR, the decreasing rate of coal consumption slows down, and so as those of SRV gas and oxygen consumption. The quality of the reformed gas with low reduction potential also becomes unsuitable for other applications. As a reference for the actual production, the recommended 55% of PCR can be adjusted according to the practical situation.

3.3. Effect of PMR in RHF

The effect of PMR on coal consumptions is shown in Fig. 12. As it can be seen in Fig. 12, more coal is needed for the increase of PCR.

Heat loss exists in each part of the process including the heat loss of the furnace itself and the heat loss during the heat recovery of the RHF exhaust gas and SRV slag. The values of absolute heat loss are 20%, 10% and 10% of the total output heat of RHF, SRV and GRF, 30% of sensible heat of RHF exhaust gas, and 50% of sensible heat of SRV slag. The relative heat loss is the percentage that heat loss takes from the total output heat. The total absolute heat loss decreases with the increase of SRV PCR as shown in Fig. 11 where ce is the abbreviation of coal equivalent and 1 kg ce corresponds to 29,270 kJ. Figure 11 also indicates that the relative heat loss increases with the increase of PCR. As a result, the absolute heat loss is reduced, but the heat utilization ratio is also reduced.

In conclusion, the recommended PCR is 55% and it is used in the following calculations. The relative and the absolute heat loss are at moderate levels. With further increase of PCR, the decreasing rate of coal consumption slows down, and so as those of SRV gas and oxygen consumption. The quality of the reformed gas with low reduction potential also becomes unsuitable for other applications. As a reference for the actual production, the recommended 55% of PCR can be adjusted according to the practical situation.
reduction of the pellet in the RHF and the coal consumption increases with the increase of PMR. Higher metallization rate reduces the energy requirement of SRV for the melting and reducing of pellet. So less coal will be needed in the SRV and the SRV gas generation and oxygen consumption are reduced in the meanwhile as shown in Fig. 13. With the same gas PCR and temperature, less SRV gas leads to less coal consumption in GRF. Thus, the total coal consumption is reduced with the increase of PMR.

Figure 14 shows that high PMR reduces the absolute quantity of heat loss but increases the relative heat loss. So the recommended PMR is 80% to balance the raw material consumption and heat loss.

3.4. Zoned Model of SRV

SRV is installed with coaxial oxygen-coal lances in the upper and lower slag zones separately to produce gas with certain PCR during operation. The metallized pellets melt in the upper slag, and then iron oxides and molten iron spread in the slag and move to the next slag layer for final reduction. So the gas PCR should be limited in order to avoid the reoxidation of metallic iron in the slag. Figure 15 shows the equilibrium diagram of iron oxides reduction which is calculated based on the data from the literature.10–12) One can see from the figure that, in the SRV temperature range (<1 650°C), the reoxidation will not happen when the gas PCR is lower than 15%.

The heat transfer efficiency of the post combustion in the top free space is 80%, but that inside the upper or lower slag zones is 100%. So the zoned model can be verified by the overall static model by setting the PCR of upper and lower slag as 0%. The temperature gradient should be existed in the slag, so the temperature of the upper slag is set as 1 600°C, and the lower slag temperature is 1 550°C. Because the output temperature of the slag is determined by the lower slag temperature, the temperature of the upper slag has no effect on the total coal consumption. The PCR of the gas in the top free space is set as constant of 55%, and the PMR is 80%. Figure 16 shows the results of the verification and the values in the brackets are the differences between the zoned and overall model. It can be seen that the calculation results of the zoned and overall model have achieved good agreement. The differences are the accumulation error brought by the coupling calculation between modules and iteration in the modules. In Fig. 16, US and LS represent the upper slag and lower slag respectively. The pellet in Fig. 16 represents the metallized pellet whose chemical composition is shown in Fig. 6. The chemical compositions of the upper and lower slags are listed in Table 4.

Calculations are made to investigate the effect of PCR on the coal and oxygen consumption of each reaction zone under the conditions of 1: PCR in the lower slag as constant of 0% and PCR in the upper slag changing from 0–15%; 2: PCR in the upper slag as constant of 15% and PCR in the lower slag changing from 0–15%. Figure 17 shows the effect of PCR on the SRV coal consumption. When the PCR in the lower slag is constant, the coal consumption of the lower slag zone is nearly the same as the sensible heats of the slag and iron droplet from upper slag are fixed. High PCR of upper slag increases the total heat generation of post combustion. Thus the coal consumption in the upper slag decreases with the increase of PCR in the upper slag, and so as the total coal consumption of SRV as shown in Fig. 17. The SRV coal consumption does not change with the increase of PCR in the lower slag while setting the upper slag PCR as constant of 15% as shown in Fig. 17. This is because that, the total heat required in the SRV is fixed, and the heat generated from coal is determined by the total PCR.
in the upper slag before the gas going to the top free space. As the PCR in the upper slag is constant, the same amount of coal will be needed to meet the heat requirement of SRV. It is just attributed to this causality that the two-level lances in the slag can flexibly realize the smelting reduction when the heat transfer is not sufficient from the upper slag, i.e. the PCR in the lower slag can be increased to supply heat directly with no change in the total coal consumption.

The effect of PCR on the percentage of coal consumption in upper and lower slag zones of SRV is shown in Fig. 18. When PCR in the lower slag is constant, the percentage of the coal consumption in lower slag increases slightly due to the slight decrease of coal consumption in the upper slag. When PCR in the upper slag is constant, the percentage of the coal consumption in lower slag decreases significantly with the increase of the PCR in the lower slag. When the PCR in the lower slag increases, less coal is needed for the required heat in the lower slag and less gas is supplied to upper slag. So more coal will be needed in the upper slag to meet the heat requirement of the upper slag, and the percentage of the coal consumption in the upper slag increases with the increase of the PCR in the lower slag.

Figure 19 shows the effect of PCR on the percentages of oxygen consumption in top free space, upper and lower slags. When PCR in the lower slag is constant, the percentage of oxygen consumption in the lower slag is also roughly constant, and that in the upper slag increases with the increase of the PCR in the upper slag. When PCRs in the upper slag and in the top free space are constant, the change rule of the percentage of oxygen consumption in the upper slag...
and lower slags is basically the same as the change of the percentage of coal consumption. So the effect of PCR in the upper slag is mainly on the percentage of oxygen consumption in the top free space and upper slag, and the effect of PCR in the lower slag is mainly on the percentage of coal consumption in the upper and lower slags.

High PCR in the upper slag reduces the coal consumption in the SRV and increases percentage of oxygen consumption in the upper slag which guarantees the heat transfer efficiency of post combustion in the top space by enhancing the stirring of the upper slag. So the recommended PCR in the upper slag is 15%. Although the increase of PCR in the lower slag can increase the percentage of coal and oxygen consumption in the upper slag which will enhance the stirring action of the upper slag, the CO₂ and H₂O in the lower slag will increase the risk of the reoxidation of the iron droplets in slag and the hot metal. So the recommended PCR in the lower slag is 0%. Under such conditions, the coal consumption of the SRV is 1 431.1 kg; oxygen consumption is 2 311.27 kg, gas generation is 4 401.03 kg; the percentages of coal consumption in upper and lower slag are 67% and 33% respectively; and the percentage of oxygen consumption in top free space, upper and lower slag are 39%, 47% and 14%, respectively. Comparing with the overall model, the coal consumption is decreased by 93.4 kg; oxygen consumption is decreased by 163.8 kg; and gas generation is decreased by 256.04 kg. As the basic operation conditions in the SRV are not changed, the result of the zoned model is a modification for the result of SRV in the overall static model, and it is more accurate to describe the mass and heat consumption of the SRV.

When the PCR of the lower slag is 0%, there is 14% oxygen need to be blown into the lower slag. In order to avoid the reoxidation in the lower slag, the coal-only injection is desirable in the lower slag. In such a case, the required heat in the lower slag need to be supplied by increasing the upper slag temperature and decreasing the lower slag temperature. The effect of slag temperature on the oxygen consumption in the lower slag is calculated and the results are shown in Fig. 20. The oxygen consumption decreases with the decrease of lower slag temperature and the increase of the upper slag temperature. The data all fits well as linear relationship, so the temperature of the slag with 0 kg oxygen consumption in the lower slag can be calculated by the fitted function and the results are shown in Fig. 21. The relationship between the upper slag temperature and the lower slag temperature is linear, so the temperature can be predicted by the linear equation when one of the temperature is given. The predicted data are verified by the zoned model and the corresponding mass and heat consumption in each zone can be calculated. As it can be seen in Fig. 21 that the temperature gradient between the upper and lower slag increases to about 133°C, and it is a necessary condition to realize the coal-only injection operation.

According to the calculation results of the Factsage™ 6.1, the temperature of the slag in this paper should be higher than 1 516°C to maintain a stable liquid phase. So if the temperature of the lower slag is set to be 1 530°C, the upper slag temperature should be 1 663°C to realize the smelting reduction process with no oxygen in the lower slag. Then, the total coal consumption of SRV is 1 443.6 kg; oxygen consumption is 2 333.24 kg; gas generation is 4 435.33 kg; the percentage of upper slag coal is 89%; and the percentages of oxygen consumption in the top free space and upper slag are 39% and 61% respectively. Comparing with the results of upper slag temperature of 1 600°C and lower slag temperature of 1 530°C, the smelting efficiency is improved and the problem of iron droplets reoxidation in the lower slag is avoided.
slag temperature of 1550°C, the SRV coal consumption increases by 12.5 kg; oxygen consumption increases by 21.97 kg; and gas generation increases by 34.3 kg.

4. Conclusion

An overall model was established to calculate the mass and heat consumptions of the entire process. The total coal consumption and gas generation are both decreased with the increase of PCR and PMR, but the relative heat loss increases at the same time. The temperature and reduction potential of the reformed gas decreases with the increase of PCR. The recommended values of PCR and PMR are 55% and 80% respectively, to balance the raw material consumption and heat loss. To produce 1 t hot metal, 3625.54 kg alumina-rich metallized pellet is needed, along with 2057.97 kg lime, 1524.5 kg coal, and 2475.07 kg oxygen, and the exhaust gas generation is 4657.07 kg. About 1 t Al₂O₃ can be recovered from the slag.

A zoned model of SRV was established to make further optimization of its operation condition. The SRV coal consumption decreases with the increase of PCR in the upper slag layer, and does not change with the increase of PCR in the lower slag. The percentage of oxygen consumption in the top free space and upper slag is determined by PCR in the upper slag, and percentage in the upper slag increases with increase of PCR in the upper slag. The percentage of coal consumption in the upper and lower slag is determined by the PCR in the lower slag, and the percentage in the upper slag increases with the increase of PCR in the lower slag. When the PCR is limited below 15% in the slag, and the heat transfer efficiency of the post combustion in the top free space is 80%, the recommended PCRs in the upper and lower slag are 15% and 0% respectively, which will decrease the coal consumption by 93.4 kg, oxygen consumption by 163.8 kg, and gas generation by 256.04 kg comparing to the overall model. The coal-only injection in the lower slag is recommended. One possible condition is that the temperatures of the upper and lower slag are 1663°C and 1530°C respectively, and the coal consumption increases by 12.5 kg, oxygen consumption by 21.97 kg, and gas generation by 34.3 kg comparing to the zoned model results with the upper slag temperature of 1600°C and lower slag temperature of 1550°C.

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