Operation Characteristic of Super-Large Blast Furnace Slag in China

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Operational smoothly of ironmaking process is determined to a great extent by its slag performance especially for the large blast furnace. Operation characteristic of super-large blast furnace slag in China was summarized and the appropriate adjustment measures for better performance of BF were analyzed based on the operation characteristic by using the MPE. The results show that MgO content ranges from 6.5–9.5 wt% and Al2O3 ranges in 11–16 wt% of the super-large blast furnaces. The hot metal temperature ranges between 1 490–1 520°C and C/S is controlled within 1.12 to 1.24. A slag operation concept is built for reference by the operation viscosity and the superheat temperature. The operation viscosity is 0.34±0.02 Pa·s and the superheat temperature is 80±10°C. Based on this, Mg/Al ratio can be reduced with the increasing C/S in the production. Mg/Al ratio of 15 wt% Al2O3 slag can be reduced to 0.4 in the high basicity of 1.3 and should be increased to 0.67 in the low basicity of 1.1. Mg/Al ratio of 0.53 (8 wt% MgO) is ideal if the basicity of slag changes in a wide range near 1.2. The rational Mg/Al ratio of the slag (C/S=1.2) can be reduced to 0.33, 0.47 and 0.58 when the Al2O3 in the slag are 12 wt%, 15 wt% and 18 wt%, respectively.

KEY WORDS: super-large blast furnace; slag; viscosity; superheat temperature; Mg/Al.

1. Introduction

Enlarging the effective volume of blast furnace (BF) will be the main tendency in China in consideration of the economic conditions, environmental pressures and market requirements in future.1) Recently, super-large BFs (larger than 4 000 m3, the same as below) are becoming an important symbol of ironmaking development, and the super-large BFs have some technology advantages in energy saving and emission.2) The super-large BFs have achieved low carbon smelting and smooth operation. In addition, molten slag has a significant effect on the stability and productivity of BF operation. Therefore, analyzing and understanding the characteristic of large-scale BF slag has an important guide for the optimization of BF slag. In recent years, utilization of high-aluminum-content iron ore has increased the content of Al2O3 in the slag. It is important to analyze the slag properties of BF slag with different Al2O3 content for maintaining stable BF operations. Much of attentions have been paid on the final slag viscosity due to its great effect on understanding the fluid dynamic of molten slag during the pyrometallurgy process. Zhang et al.3) studied the effect of Mg/Al ratio on the viscosity, the stability and break point temperature of BF slag. The rational of Mg/Al was recommended in a range of 0.6–0.7 in the high Al2O3 content. Shiu et al.4) indicated that the lower liquidus temperature and the better viscosity stability laid in the area of MgO = 5.4 wt%, Al2O3 = 10–15 wt%, and C/S (CaO/SiO2) = 1.2. Lu et al.5) investigated that the viscosity and the melting temperature of the slag. The appropriate Mg/Al ratio was among 0.90 to 0.75. Shen et al.6) considered that the suitable Mg/Al was 0.2–0.5 based on the analysis of the slag viscosity and assuming the melting temperature of molten slag was 1 400±25°C. Thus, different researches had different opinions on the ratio of Mg/Al ratio. However, the previous study were based on the laboratorial experiments. Few researches regarded to the viscosity and liquidus temperature of the actual operation characteristic of BF slags with various compositions and temperature.

Moreover, a number of viscosity models have been developed to predict the viscosity of the SiO2–Al2O3–CaO–MgO (typical BF slag components) system over the last decades. These viscosity models can be generally classified into two groups, empirical models and structural models.7–12) The Multi-Phase Equilibrium (MPE) is a thermodynamic package developed by CSIRO for simulating reactions between phases in multi-component and multiphase systems.13–15) Through application of the thermodynamic model MPE, the viscosity and liquidus temperature of BF slags were calculated and compared with published experimental data. These comparisons showed the predicted values by the

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model were to be in good agreement and within experimental uncertainty.

In order to specify the actual operation characteristic of the super-large BF slag, the characteristic of Chinese super-large BFs slag with different compositions and temperature were conducted based on the actual production data by using MPE. The objective of this study is to evaluate the operation characteristic of super-large BFs slag and find the appropriate adjustment measures for better performance of BF.

2. Current Operation of Chinese Super-large BF Slag

2.1. Overview of Chinese Super-large BFs in Operation

The development of Chinese super-large BF started late and entered in the flourishing period during the last ten years. In recent years, by Chinese super-large BF operators’ continuous efforts, the BF production indexes were improved constantly, and fuel rate was declined ceaselessly. At present, there are 21 super-large BFs running in China, as shown in Table 1. The BFs are ordered by the effective volume.

The description appears in Table 2 and Fig. 1 showing the slag compositions and hot metal temperature ($T_{HM}$) of the Chinese super-large BFs. $C/S$, Mg/Al ratio decreases with increasing $C/S$. In addition, $T_{HM}$ also illustrates the relationship between $C/S$ and Mg/Al ratio based on the slag analysis of Chinese super-large BFs. Mg/Al ratio ranges from 0.45 to 0.7. MgO content in the slag is among 6.5–9.5 wt% and Al2O3 ranges in 11–16 wt%. It also illustrates that the temperature of hot metal ($T_{HM}$) are various, which ranges among 1 490–1 520°C.

**Figure 2** illustrates the relationship between $C/S$ and Mg/Al ratio based on the slag analysis of Chinese super-large BFs. Mg/Al ratio decreases with increasing $C/S$. In addition, all of the BFs including BFs with low Mg/Al ratio are in the condition of smooth operation. Thus, it is possible to be concluded that the BF can also achieve a smooth operation.

### Table 1. Overview and production indexes of Chinese super-large BFs in operation.

<table>
<thead>
<tr>
<th>Furnace No.</th>
<th>Effective volume m$^3$</th>
<th>Commissioning date</th>
<th>Hearth diameter m</th>
<th>Productivity t/(m$^3$·d)</th>
<th>[Si] wt%</th>
<th>Fuel rate kg/tHM</th>
<th>Coal rate kg/tHM</th>
<th>Slag Volume kg/tHM</th>
</tr>
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<tr>
<td>1</td>
<td>Shagang</td>
<td>5 800</td>
<td>2009.10.20</td>
<td>15.3</td>
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<td>184</td>
</tr>
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<td>2009.5.21</td>
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<td>498</td>
<td>153</td>
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<td>2.26</td>
<td>0.38</td>
<td>498</td>
<td>154</td>
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<td>4</td>
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<td>5 050</td>
<td>2015.9.25</td>
<td>14.5</td>
<td>2.28</td>
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<td>490</td>
<td>180</td>
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<tr>
<td>5</td>
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<td>2.28</td>
<td>0.39</td>
<td>477</td>
<td>180</td>
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<td>492</td>
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<td>7</td>
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<td>2.11</td>
<td>0.39</td>
<td>487</td>
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<td>9</td>
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<td>0.45</td>
<td>494</td>
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<td>1.85</td>
<td>0.25</td>
<td>542</td>
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<td>2009.8.1</td>
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<td>0.48</td>
<td>504</td>
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<td>17</td>
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<td>4 070</td>
<td>2012.6.2</td>
<td>15.5</td>
<td>2.24</td>
<td>0.47</td>
<td>496</td>
<td>140</td>
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<td>18</td>
<td>Angang Bayuan No. 2</td>
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<td>2008.9.6</td>
<td>13.3</td>
<td>2.20</td>
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<td>2007.5.8</td>
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<td>2.17</td>
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<td>548</td>
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<td>0.39</td>
<td>508</td>
<td>155</td>
</tr>
</tbody>
</table>
with low Mg/Al ratio in the high basicity (C/S) condition.

2.2. Characteristic of Chinese Super-large BFs Slag

The bad permeability for liquid flow is usually caused by the bad slag fluidity, which can be expressed by using the indexes such as slag liquidus temperature and viscosity. The developed MPE are used in the calculation of all the Chinese super-large BFs slag to present the characteristic of slag fluidity.

| Fig. 1. Slag compositions and hot metal temperature (\(T_{HM}\)) of Chinese super-large BFs. |
| Fig. 2. Relationship between the C/S and Mg/Al ratio of Chinese super-large BFs slag. |
| Fig. 3. Viscosity, liquidus temperature and superheat temperature of Chinese super-large BFs slag. |

Figure 3 shows the operation viscosity (slag viscosity in the temperature of hot metal) and liquidus temperature of the slag estimated based on the actual slag chemical compositions. In terms of the Chinese super-large BFs, the operation viscosity of the slag ranges from 0.29 to 0.38 Pa·s and the average of the operation viscosity is 0.34 Pa·s in the various temperatures and slag compositions. The liquidus temperature ranges from 1380 to 1440°C and the slag composition varies in a relative wide range, which means that a lower and a higher liquidus temperature could obtain in the complex BF operation. In the actual BF, there is a temperature distribution and a composition distribution in the furnace lower part and thus, a slag operation concept.
is needed for the guidance of BF slag operation. In the present study, the difference between the hot metal temperature and the slag liquidus temperature are calculated and named as superheat temperature. The higher the superheat temperature is, the better the slag flows. The BF can have a smooth operation with fluidly slag. Superheat temperature of the super large BFs range in a small scale between 70–90°C excluding four of the BFs although both the liquidus temperature and hot metal temperature fluctuate in a wide range.

Moreover, comparing Figs. 4(a), 4(b), and 4(c), the operation viscosity and the liquidus temperature of the actual BF slag are influenced by many factors. Operation viscosity and liquidus temperature are the results of comprehensive influence by the hot metal temperature and slag compositions. However, the operation viscosity appears to be more pronounced by the hot metal temperature, which is the dominant factor for operation viscosity. The slag liquidus temperature fluctuates with the hot metal temperature and shows a great influence on the C/S and Mg/Al ratio.

Based on the analysis of the Chinese super-large BFs slag in the production, a slag operation concept is built for reference by the operation viscosity and the superheat temperature. The operation viscosity and the superheat temperature of the Chinese super-large BFs slag are 0.34±0.02 Pa·s and 80±10°C, respectively.

3. Optimization of BF Slag

3.1. Rational Mg/Al

The effects of MgO on the superheat temperature and operation viscosity have been evaluated by using MPE for slags having basicity (C/S) of 1.2 various levels of Al2O3. The Al2O3 content was fixed at 12, 15 and 18 wt% while MgO was increased from 4 to 12 wt%. Figure 5 shows that the addition of MgO can alter the superheat temperature quite significantly depending on the concentration of Al2O3. It indicates that at low Al2O3 contents (12 wt%), the slag is in melillite (an aluminosilicate solid solution phase) saturated region and the liquidus temperature decreases with increasing MgO. The superheat temperature decreases with MgO higher than 9 wt% and enters into a region of Ca2MgSi2O6 saturation. It is clear that at high Al2O3 contents (15 and 18 wt%), the increasing MgO leads to increase the superheat temperature of the slag.

The viscosities of slags with basicity (C/S) of 1.2, Al2O3 content of 12–18 wt% and MgO of 4–12 wt% are calculated at 1 500°C. Figure 5 shows that the viscosity of the slag increases with increasing the Al2O3 content. The trend was supported by the experimental data.21–26 The slag with high Al2O3 will lead to less fluidity of the slag, hence affect the BF operation. As marked in Fig. 5, with the Al2O3 increasing from 12 to 18 wt%, the slag viscosity can be maintained at the same level by increasing the MgO level.

Figure 5 also gives the range of superheat temperature and operation viscosity of the BF operation area. When Al2O3 is 12 wt% and MgO is lower than 10 wt%, the superheat temperature is above the operation range. When MgO is higher, the viscosity of the slag is lower than the operation range. So the BF can have a smooth operation when MgO varies from 4–12 wt%. However, in order to have a lower carbon consumption, the hot metal temperature can be reduced to a lower level than 1 500°C.

When Al2O3 is 15 wt%, the viscosity is not in the operation range as MgO is lower than 7 wt% and the superheat temperature is not in the operation range as MgO is higher than 10 wt%. So the rational MgO is 7–10 wt%. And the corresponding Mg/Al is 0.47–0.67. When Al2O3 is 18 wt%, the superheat temperature is higher than the operation range as MgO is lower than 10.5 wt% and the viscosity is also higher than the operation range as MgO is lower than 10.5 wt%. Therefore, the BF slag is reasonable when MgO is higher than 10.5 wt%. The corresponding Mg/Al is 0.58. And it is a good measure to reduce the Mg/Al ratio further by increasing the hot metal temperature.

3.2. Effect of C/S on the Viscosity and Superheat Temperature

The effects of basicity (C/S) on the viscosity and superheat temperature have been evaluated by using the MPE for slags with various levels of MgO. The Al2O3 content is fixed at 12, 15, and 18 wt% while the corresponding hot metal temperature are 1 490°C, 1 500°C and 1 510°C. Figure 6 shows the calculation results of 12 wt% Al2O3. A lower C/S corresponds a higher slag viscosity and higher superheat temperature regardless of the MgO content. The slag viscosity as well as superheat temperature decreases with the increasing MgO. It indicates that MgO in the slag can be a relative low lever (4–8 wt%) when the basicity is high at 1.3. When the basicity is low at 1.1, the MgO should be increased to 10–12 wt% to have a smooth operation.

The viscosity and superheat temperature at 15 wt% Al2O3 is plotted in Fig. 7. The viscosity of the slag decrease with the increasing C/S and the variation of the superheat temperature is relative complex. The low C/S corresponds high superheat temperature and high C/S corresponds to low superheat temperature regardless of the effect of MgO. It indicates that the effect of viscosity is more pronounced than the effect of superheat temperature as the range area of viscosity is much narrower. Mg/Al ratio in the slag can be reduced to 0.4 in the high basicity of 1.3 and should be increased to 0.67 in the low basicity of 1.1. The Mg/Al ratio of 0.53 (8 wt% MgO) is ideal if the basicity of slag changes in a wide range near 1.2.
As illustrated in Fig. 8, when Al$_2$O$_3$ content is 18 wt%, the viscosity decreases with the increasing C/S and the superheat temperature varies in a wider range. Many of the viscosity and superheat temperature values are not in the operation range when MgO is lower than 10 wt%. So it is much more difficult to have a smooth operation at low Mg/Al ratio. When MgO content is above 10 wt%, the viscosity and superheat temperature can satisfy the requirement of BF operation and the Mg/Al ratio is 0.56.

3.3. Optimization Strategies for Actual BF Slag
As a result of the complicated changes of the actual parameters in BF production, it is difficult to find the unified regularity. In order to specific the optimization of Chinese
super-Large BF slag, No. 13 BF is taken as an example. Only the influence of single factor of the slag composition or hot metal temperature on the slag characteristic is analyzed in the following respectively and individually.

Calculation values of the viscosity and superheat temperature of No. 13 are shown in Fig. 9. From Fig. 9(a), the temperature of the hot metal can be reduced to the range that the superheat temperature and the viscosity can satisfy the requirement of the No. 13 BF slag. Thus, in the BF slag composition range of the study, the temperature can be reduced by almost 20°C. From Fig. 9(b), MgO can be reduced for the viscosity of the slag is lower and the superheat temperature is higher than the specific area. By reducing MgO content from 7.0 to 4.0 wt%, the superheat temperature of No.13 slag can be decreased. With the decreasing MgO, the slag volume of the BF operation can be obtained at a lower level, which can result in the lower fuel ratio and higher productivity. Figure 9(c) illustrates the effect of C/S ratio on the slag viscosity and the superheat temperature. With C/S of the slag increasing from 1.1 to 1.25, the viscosity is found to first decreases rapidly and then increases, and then decreases. The viscosity decreases largely with C/S increasing. It suggests that C/S can be adjusted in a wide range. Figure 8(d) shows the effect of Al$_2$O$_3$ content on the viscosity and the superheat temperature of slag. Slag viscosity increases and superheat temperature decreases with increasing Al$_2$O$_3$ content at a fixed temperature. In order to reduce the production cost, the low price ore with higher Al$_2$O$_3$ can be partly used, which has small influence on the slag operation and BF can also be smooth operation at a lower cost. Therefore, the optimization strategies for actual BF slag can be obtained through the concept of operation viscosity and superheat temperature.

4. Conclusions

Operation characteristic of super-large BF slag in China was summarized and the appropriate adjustment measures for better performance of BF were evaluated. The conclusions of the present work can be drawn as follows:

1) The average data of Chinese super-large BF slag are summarized. MgO content ranges from 6.5–9.5 wt% and Al$_2$O$_3$ ranges in 11–16 wt%. The hot metal temperature ranges between 1 490–1 520°C. C/S is controlled within 1.12 to 1.24 and the Mg/Al is ranged from 0.45 to 0.7. Mg/Al ratio reduced with the increasing C/S.

2) The operation characteristic of super-large BF slag is identified based on the analysis of slag properties of production data. A slag operation concept is built for reference by the operation viscosity and the superheat temperature. The operation viscosity is 0.34±0.02 Pa·s and the superheat temperature is 80±10°C.

3) In the condition of C/S is 1.2, the rational Mg/Al is 0.58 and can be reduced further by increasing the hot metal temperature when Al$_2$O$_3$ is 18 wt%. The rational Mg/Al is 0.47 when Al$_2$O$_3$ is 15 wt%. When Al$_2$O$_3$ is 12 wt%, the rational Mg/Al can be 0.33 and the hot metal temperature can be reduced to a lower level than 1 500°C.

4) The rational Mg/Al changes with C/S. Mg/Al ratio is found to first decreases rapidly and then increases, and then decreases. The viscosity decreases largely with C/S increasing. It suggests that C/S can be adjusted in a wide range. Figure 8(d) shows the effect of Al$_2$O$_3$ content on the viscosity and the superheat temperature of slag. Slag viscosity increases and superheat temperature decreases with increasing Al$_2$O$_3$ content at a fixed temperature. In order to reduce the production cost, the low price ore with higher Al$_2$O$_3$ can be partly used, which has small influence on the slag operation and BF can also be smooth operation at a lower cost. Therefore, the optimization strategies for actual BF slag can be obtained through the concept of operation viscosity and superheat temperature.

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