Influence of B$_2$O$_3$ on Viscosity of High Ti-bearing Blast Furnace Slag

Shan REN, Jianliang ZHANG, Liushun WU, Weijian LIU, Yanan BAI, Xiangdong XING, Buxin SU and Dewen KONG

1) State Key Laboratory of Advanced Metallurgy, University of Science & Technology Beijing, Beijing, 100083 China. E-mail: jeopardize@126.com 2) Formerly Graduate Student, Royal Institute of Technology. Now at Anhui University of Technology, Maanshan, 243032 China. E-mail: wuliushun@yahoo.cn

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The influence of B$_2$O$_3$ on the viscosity of high Ti-bearing BF slag is studied under Ar atmosphere from 1 773 K (1 500°C) to about 1 593 K (1 320°C). The results show that the addition of B$_2$O$_3$ can decrease the viscosity of high Ti-bearing BF Slag containing UPC, consequently improve its fluidity. With the existence of 1.5% UPC, when the content of B$_2$O$_3$ increased from 0 to 4.1%, the volume fraction of perovskite decreased from 7.7% to 1.6% at 1 610 K. Meanwhile, the liquidus temperatures decreased from 1 619 K to 1 613 K. At a lower temperature, B$_2$O$_3$ was easy to form a eutectic and decreased the viscosity of molten slag. At a higher temperature, some tetrahedron [BO$_4$]$^{5-}$ changed into triangle [BO$_3$]$^{3-}$ which would disintegrate the chains/molecules of molten matrix and decreased its viscosity.

KEY WORDS: Ti-bearing blast furnace slag; viscosity; B$_2$O$_3$.

1. Introduction

Nowadays, Pulverized Coal Injection (PCI) is one of the most effective technologies to reduce coke consumption in Blast Furnace (BF). Increasing PCI rate and decreasing total fuel rate in BF is a promising and realistic alternative in the current ironmaking process in China. But at large PCI rate, some Unconsumed Pulverized Coal (UPC) might accumulate in the hearth of BF or escape along with the off-gases from the top of furnace, which lead to deterioration of the burden permeability and unstable furnace operation.\(^1\,^2\) Especially, the blast furnace slag of Panzhihua Iron and Steel Corporation (PANGANG) contains approximately 22–25% TiO$_2$, and TiO$_2$ will be reduced by UPC and produce a certain amount of TiC, TiN and Ti(C,N). These Ti subcompounds have high melting temperature, which will make the slag have even higher viscosity and hard to be separated from hot metal at the taphole.\(^3\,^4\) So it becomes extremely significant to increase the fluidity of high Ti-bearing blast furnace slag which contains UPC.

H. G. Du et al. have studied the additives of FeO, SiO$_2$, MnO and V$_2$O$_5$ in high Ti-bearing slag of blast furnace to inhibit TiO$_2$ reduction.\(^5\,^6\) The results indicate that these additives can inhibit TiC, TiN and Ti(C,N) emergence to some degree because FeO, SiO$_2$, MnO and V$_2$O$_5$ have higher oxygen potential than TiO$_2$ in oxygen-potential diagram, and they are easier to be reduced than TiO$_2$, but they can’t improve the fluidity of the slag fundamentally.

T. Hamano et al. have studied the effect of B$_2$O$_3$ on dephosphorization of molten steel by FeO$_{\alpha}$–CaO–MgO$_{\alpha}$–SiO$_2$ slag at 1 873 K.\(^7\,^8\) M. Nakamoto et al. have studied the evaluation of B$_2$O$_3$ on surface tension of molten silicates.\(^9\) Z. T. Zhang et al. have investigated evaporation of B$_2$O$_3$ and Na$_2$O in F-free mold slags.\(^10\) H. M. Wang et al. have investigated the effect of B$_2$O$_3$ on melting temperature, viscosity and desulfurization capacity of CaO–based refining flux.\(^11\) All these studies have indicated that B$_2$O$_3$ is a kind of lubricant and can increase the fluidity of metallurgical slag. The primary concerns of previous studies are to identify the effect of B$_2$O$_3$ on refining flux and F-free mold slag. Hitherto, there is not a report on reducing viscosity of high Ti-bearing BF slag using B$_2$O$_3$. In this context, the present work aims to investigate the effect of B$_2$O$_3$ on the viscosity of CaO–SiO$_2$–MgO–Al$_2$O$_3$–TiO$_2$ (–B$_2$O$_3$) slags from 1 773 K (1 500°C) to about 1 593 K (1 320°C) with addition of UPC.

2. Experimental

2.1. Materials, Apparatuses and Equipments

Materials: These slags were synthesized based on the master component of PANGANG BF slag, and the chemicals used in the experiments such as CaO, SiO$_2$, TiO$_2$, Al$_2$O$_3$, MgO, B$_2$O$_3$ were all analytical reagent. UPC is replaced with pure graphite powder. The grain size of graphite powder is in the range of 8.39–91.09 μm and its mean grain size is 31.53 μm. The grain size distribution of graphite powder is shown in Fig. 1. The content of B$_2$O$_3$ in the slags changed from 0 mass % to 4.5 mass % (Table 1).

Apparatuses and Equipments: The experimental setup for the viscosity measurement is schematically shown in Fig. 2. Viscosity measurement was carried out by the rotating cylinder method using a Brookfield digital viscometer. An elec-
A resistance furnace equipped with six U-shape MoSi₂ heating elements was employed. Meanwhile, the furnace could be moved along the vertical direction by a hydraulic moving system. The experimental temperatures were controlled by a Pt - 6% Rh / Pt - 30% Rh thermocouple inserted into the furnace with an error less than $\pm 2$ K. The viscometer was calibrated using standard silicone oil (error is $\pm 1$ mPa.s) at $(298 \pm 1)$ K. Also, the calibration of the viscometer was made by using reference slag (SRM2 type slag) at high temperature and the viscosity could be followed by a computer as a function of time using the software supplied by Brookfield.

The molybdenum crucible and spindle were employed for the viscosity measurement. The spindle consisted of a Bob and a Shaft, and the undersides of them are closely linked. The specific dimensions were listed in Table 2.

### Table 2. Dimensions of contact materials for viscous measurement.

<table>
<thead>
<tr>
<th></th>
<th>Inner diameter (mm)</th>
<th>Inner depth (mm)</th>
<th>Base thickness (mm)</th>
<th>Wall thickness (mm)</th>
<th>Height (mm)</th>
<th>Bob diameter (mm)</th>
<th>Bob length (mm)</th>
<th>Shaft diameter (mm)</th>
<th>Shaft length (mm)</th>
<th>Degree of taper (°)</th>
</tr>
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<tbody>
<tr>
<td>Mo crucible</td>
<td>40</td>
<td>80</td>
<td>2</td>
<td>6</td>
<td>86</td>
<td>13</td>
<td>20</td>
<td>3</td>
<td>500</td>
<td>45</td>
</tr>
<tr>
<td>Mo spindle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

2.2. Experimental Procedure

The slags were prepared as follows: Firstly, the master slags containing CaO–SiO₂–MgO–Al₂O₃–TiO₂ were premelted in Mo crucible in the same electric resistance furnace. Meanwhile, low heating rate was adopted, which could slow the formation of foamed slag, and decrease the contamination of furnace chamber. Thereafter, the pre-melted master slag was quenched rapidly to avoid the expansion of the sample due to phase transformation, which would damage the Mo crucible. Secondly, B₂O₃ powder and graphite powder were added to the master slag. The mixture of master slag-B₂O₃-graphite powder was premelted again in the same furnace. B₂O₃ has a low melting point (723 K), which may result in great loss of B₂O₃ during premelting due to volatilization. Therefore, a Mo cover was put on the top of the crucible to avoid the extensive volatilization of B₂O₃ before it dissolved into the slag. Again, the sample was quenched to keep the Mo crucible from cracking. The Mo cover was not removed until the furnace was heated up again for viscosity measurements. Purified argon gas (99.99%) was applied throughout the pre-melting procedures. Each premelted slag is about 100 g.

The furnace chamber was evacuated after placing the Mo crucible on the pedestal and the Mo spindle just above the sample. Purified argon gas was then introduced from the gas inlet situated at the bottom of the furnace chamber and led out from the Ar outlet in the furnace. A low argon flow rate (about 0.03 l/min) was maintained throughout the whole experiment. The sample was heated up to a temperature of 1 773 K (1 500°C) at the rate of 5 K/min and kept there for 240 min for melting and reacting sufficiently. The furnace was moved up slowly to immerse the spindle into the liquid slag. The low rotational rate was employed to ensure homogenization of the sample sufficiently. Then the sample was cooled down slowly from 1 773 K to about 1 593 K and the viscosity-time curve was recorded by the software on personal computer. Temperature profile for present experiment is shown in Fig. 3. Each measurement was conducted after sample was kept certain temperature for 10 min. After the measurement of viscosity, the sample was heated up from 1 593 K to 1 610 K and kept the temperature for 90 min, then the sample along with the crucible was quenched for detection with very high flow rate Ar impinged on the sam-

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**Fig. 1.** Grain size distribution of graphite powder.

**Fig. 2.** Schematic diagram of the experimental apparatus.

**Table 1.** Chemical compositions of the samples (mass%).

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>CaO</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>MgO</th>
<th>TiO₂</th>
<th>C</th>
<th>B₂O₃</th>
<th>R</th>
</tr>
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<tbody>
<tr>
<td>0#</td>
<td>29.6</td>
<td>26.9</td>
<td>14.0</td>
<td>7.5</td>
<td>22.0</td>
<td>0</td>
<td>0</td>
<td>1.1</td>
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<tr>
<td>1#</td>
<td>28.8</td>
<td>26.2</td>
<td>14.0</td>
<td>7.5</td>
<td>22.0</td>
<td>1.5</td>
<td>0</td>
<td>1.1</td>
</tr>
<tr>
<td>2#</td>
<td>28.8</td>
<td>26.2</td>
<td>14.0</td>
<td>7.5</td>
<td>22.0</td>
<td>1.5</td>
<td>1.5</td>
<td>1.1</td>
</tr>
<tr>
<td>3#</td>
<td>28.0</td>
<td>25.5</td>
<td>14.0</td>
<td>7.5</td>
<td>22.0</td>
<td>1.5</td>
<td>3.0</td>
<td>1.1</td>
</tr>
<tr>
<td>4#</td>
<td>27.2</td>
<td>24.8</td>
<td>14.0</td>
<td>7.5</td>
<td>22.0</td>
<td>1.5</td>
<td>4.5</td>
<td>1.1</td>
</tr>
<tr>
<td>5#</td>
<td>26.5</td>
<td>24.0</td>
<td>14.0</td>
<td>7.5</td>
<td>22.0</td>
<td>1.5</td>
<td>4.5</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Note: R stands for binary basicity; C is pure graphite powder which stands for UPC.

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Note: R stands for binary basicity; C is pure graphite powder which stands for UPC.
ple. The sample temperature was followed by the thermocouple attached to the bottom of the crucible.

A number of pieces of the quenched sample were collected and divided into three portions. One was used to analyse the content of B$_2$O$_3$ by X-Ray fluoroscopy (XRF). One was ground finely (grain size is smaller than 74 μm) and characterized by X-ray diffraction (MXP21VAHF made in Japan MAC Science Co. Ltd). The other was machined into cubic shape, and polished sufficiently. After the treatment, the samples were characterized with SEM (JSM-6480LV made in Japan JEOL) in order to obtain some information on mineral, particle sizes and distributions of them. Meanwhile, distributions of Mg, Al, Si, Ca and Ti were obtained by surface scanning with the SEM. By analyzing some SEM images (at least 6 slides) taken from different position of sample, the rough area fraction of each mineral was obtained. The volume fraction of mineral was calculated by supposing that volume fraction of a mineral be equivalent with its area fraction based on statistic view.

Finally, the chemical compositions of mineral and matrix were characterized roughly with EDS (Noran System Six made in America). Besides, DSC method was adopted as one of methods to determine liquidus temperature of sample. Firstly, sample was heated up to 1 773 K, keeping the temperature for 20 minutes for complete melting. Then the sample cooled down at the rate of 10 K/min in the first cycle and at the rate of 5 K/min in the second cycle.

3. Results

3.1. Content of B$_2$O$_3$ after Experiment

The contents of B$_2$O$_3$ after measurement are presented in Table 3. Comparing with Table 1, it can be seen that the contents of B$_2$O$_3$ were close to the designed contents. Namely, in the process of premelting and reaction between UPC and CaO–SiO$_2$–MgO–Al$_2$O$_3$–TiO$_2$ (–B$_2$O$_3$) slags, little B$_2$O$_3$ is lost. It was negligible.

3.2. Viscosity Variation of High Ti-bearing BF Slag with B$_2$O$_3$ Content

Figure 4 shows the variation of viscosity with temperature involving the master slag with different content of B$_2$O$_3$ or UPC additives. As seen from Fig. 4, the addition of B$_2$O$_3$ decreases the viscosity of slag. In addition, the more addition of B$_2$O$_3$ leads to more viscosity decrease, but the degree of decrease is not too large. Another interesting finding is as follows: with very nearly the same content of B$_2$O$_3$, the master slag with UPC additive has higher viscosity than that without UPC, i.e., UPC in high Ti-bearing BF slag can increase the viscosity of the slag. Meanwhile, the gap of viscosity value increased correspondingly when the temperature decreased gradually. It can be seen from curve 3# and 1#. The curve of 0# slag was blank experiment result without B$_2$O$_3$ or UPC in the master slag. The curve of 1# slag was the experiment result with B$_2$O$_3$ and without UPC. From the curves of 0# and 1#, it can also conclude that the addition of B$_2$O$_3$ can decrease the viscosity of the master slag especially for lower temperature.

It can be easily found from Fig. 5 that, at higher temperature from 1 713 K (1 440°C) to 1 773 K (1 500°C), the viscosity of samples changed very slightly with the change of composition from 0# to 5# slag, but it changed obviously with the change of temperature. Therefore, change of tem-

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>B$_2$O$_3$ (mass%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0#</td>
<td>0</td>
</tr>
<tr>
<td>1#</td>
<td>1.4</td>
</tr>
<tr>
<td>2#</td>
<td>0</td>
</tr>
<tr>
<td>3#</td>
<td>1.3</td>
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<tr>
<td>4#</td>
<td>2.6</td>
</tr>
<tr>
<td>5#</td>
<td>4.1</td>
</tr>
</tbody>
</table>
perature is the main reason for change of viscosity at higher temperature.

3.3. Determination of Liquidus Temperatures

The liquidus temperatures obtained by the second derivative method and DSC measurements for all slags in this study\textsuperscript{18,19} are listed in Table 4. It can be concluded that the liquidus temperature was about 1 616 K determined by the second derivative method. Also, it should be pointed out that DSC measurements were not perfectly employed for all metallurgical fluxes. The measurements of liquidus temperatures of slags by DSC method are usually extremely difficult and unreliable because of the vital supercooling that the slags undergo. Taken during heating cycles, DSC value can

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Liquidus temperatures (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$d^2(Q/R)/dT^2$</td>
</tr>
<tr>
<td>0#</td>
<td>1 617</td>
</tr>
<tr>
<td>1#</td>
<td>1 615</td>
</tr>
<tr>
<td>2#</td>
<td>1 619</td>
</tr>
<tr>
<td>3#</td>
<td>1 615</td>
</tr>
<tr>
<td>4#</td>
<td>1 613</td>
</tr>
<tr>
<td>5#</td>
<td>1 613</td>
</tr>
</tbody>
</table>

Fig. 6. Mapping of Mg, Al, Si, Ca and Ti surface distribution in 0# slag at 1 610 K.

Fig. 7. XRD patterns of 0#, 1#, 3# and 5# slag at 1 610 K. 1: Perovskite CaTiO$_3$; 2: Diopside CaMgSiO$_3$; 3: Baikovite Ca$_{1.07}$Mg$_{0.625}$Ti$_{0.31}$((Al$_{0.55}$Si$_{0.45}$)$_2$O$_6$)(Al$_{(Mg,Ti)}$$_{2}$O$_4$); 4: Enstatite: Mg$_2$(Si$_2$O$_6$).
be higher due to compositional inhomogeneity. The second derivative method for the estimation of the liquidus temperatures depends on a certain amount of viscosity values available at different temperature intervals. Compared to DSC method, the second derivative method can give relatively reliable values for liquidus temperatures. Therefore, liquidus temperatures were determined by second derivative method in this study. The measured values of DSC method were just a reference. The higher content of B2O3 was, the lower liquidus temperature would be.

3.4. Chemical Composition and Volume Fraction of Solid and Liquid Phases in the Slags

3.4.1. Area scanning Analysis

Area scanning mappings of 0# slag were carried out to characterize the distribution of Mg, Al, Si, Ca and Ti at 1610 K which was shown in Fig. 6. From the mappings of area scanning, it can be easily seen that Ca and Ti gathered in one phase while other elements dispersed homogeneously in matrix.

3.4.2. XRD Analysis

The results of X-ray diffraction analysis of 0#, 1#, 3# and 5# samples were shown in Fig. 7. As shown in XRD pattern, main peaks correspond to XRD spectrum of perovskite, which implies that the major precipitation mineral is perovskite when the temperature was below breaking point. Besides, some weaker peaks match standard spectrum of diopside (CaMgSi2O6), baikovite (Calcium Magnesium Titanium Aluminum Silicate Oxide) and enstatite (Mg2Si2O4). The chemical formula of baikovite was Ca1.07Mg0.625Ti0.31((Al0.55Si0.45)2O6)(Al(Mg0.368Ti0.585Al0.03)2O4). However, diopside, baikovite and enstatite can’t be found in SEM images (Figs. 8 and 9).

3.4.3. SEM/EDS Analysis

Back-scattered electron images for ×100 and ×1 000 of 0#, 1#, 3# and 5# slag were shown in Figs. 8 and 9, respect-
tively. As shown in Fig. 8, the sample consisted of solid phase and liquid matrix. Rough chemical compositions of different phases (EDS analysis) were presented in Table 5. Combining BSE images with EDS analysis, it can be concluded that the phase (bigger particles) marked with “1” is solid phase and its chemical composition can be expressed roughly as CaTiO₃, i.e. perovskite (it has been confirmed by X-ray pattern in Fig. 7). The mineral disperses inhomogeneously in matrix (see Fig. 8). There are many bigger solid particles in some areas, while there are fewer bigger solid particles in other areas. By analyzing some SEM images (at least 6 slides) taken from different position of sample (including dense and sparse distribution of bigger solid particles), the rough area fraction of bigger solid particle was obtained. The phases marked with “2” and “2’” are the same glassy phase, they are liquid matrix and consisted mainly of Ca, Si, Mg, Al, Ti and O elements. It must be pointed out, besides bigger solid particles and liquid matrix, there are large quantities of micro fishbone like particles which can be called dendritic crystal distributing in matrix and they are marked with “3’”. The dendritic crystal precipitate during quenching due to quenching rate is not sufficient. However, it is easy to identify bigger particles (exist at 1610 K) and dendritic crystal (precipitate during quenching) in Figs. 8 and 9. The amount of dendritic crystal is large in slags and the distribution of it can be seen clearly in Fig. 10. Furthermore, diopside, baikovite, enstatite and perovskite are in the dendritic crystal (rough calculation by EDS analysis), so they can be found in XRD pattern. In the process of calculation of volume fraction of solid-liquid phase, just bigger particle (precipitate at 1610 K) was considered, so the volume fraction of solid-liquid phase was not high in Table 5. Both (c) and (d) figures (see Fig. 9) contained a little TiC

Table 5. Chemical compositions and quantities of melting slag at 1610 K.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Chemical composition (mass %)</th>
<th>Liquid phase</th>
<th>Solid phase</th>
<th>Volume fraction (vol %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CaO</td>
<td>SiO₂</td>
<td>MgO</td>
<td>Al₂O₃</td>
</tr>
<tr>
<td>0#</td>
<td>27.2</td>
<td>30.7</td>
<td>8.5</td>
<td>16.3</td>
</tr>
<tr>
<td>1#</td>
<td>26.9</td>
<td>29.7</td>
<td>8.3</td>
<td>15.8</td>
</tr>
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<td>2#</td>
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<td>31.6</td>
<td>8.8</td>
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<td>5#</td>
<td>26.0</td>
<td>28.4</td>
<td>8.6</td>
<td>15.9</td>
</tr>
</tbody>
</table>
particle which was marked with “3”. Meanwhile, some small holes can be seen in fracture surface of 3# and 5# slag. In brief, sample mainly contains two phases: perovskite and liquid matrix at 1 610 K.

4. Discussions

Based on Fig. 4 and Table 5, it can be concluded that, with the increase of B2O3 addition, volume fraction of solid phase decreased at 1 610 K which was slightly lower than the liquidus temperature (about 1 616 K). Correspondingly, the viscosity of high Ti-bearing blast furnace slag decreased gradually. At higher temperature (above 1 620 K), the moderate viscosity increase with the decrease of temperature and the absence of discontinuity of the viscosity-temperature curves suggested that these slags were all liquid. Combining with Fig. 9, it can be found that a small quantity of TiC can form in the molten slag due to the existence of UPC. In fact, a little TiC dispersing in slag has a slight effect on the viscosity of slag at high temperature.

The influence of B2O3 on molten matrix was as follows:20–22) at lower temperatures, boron appeared with boron oxygen tetrahedron [BO]5−, which should have made the viscosity of molten slag increase. However, B2O3 was easy to form a eutectic which was even more powerful to decrease the viscosity of molten slag. On the whole, the viscosity of molten slag decreased at the temperatures. At a high temperature, besides the effect of temperature on viscosity, some tetrahedron [BO]5− changed into triangle [BO]3− which would disintegrate the chains/molecules of molten slag and made the structure of molten matrix become loose, so the viscosity would further decreased. Therefore, when the temperature was below 1 610 K, the viscosity of all the slags increased sharply, still, the viscosity was lower for higher content of B2O3 at the same temperature.

The addition of B2O3 restrained the precipitation of solid phase, thereby decreasing viscosity. At 1 610 K, with the existence of UPC, when the content of B2O3 increased from 0 to 4.1%, the solid fraction decreased from 7.7% to 1.6%. Therefore, with the increase of B2O3 addition, the solid fraction decreased and the viscosity of the slag decreased. A comparison of curves 2–5# in Fig. 4 indicated that the addition of B2O3 can decrease the viscosity of master slags. The more content of B2O3 was, the lower viscosity of slag would be.

As mentioned above, the existence of B2O3 restrained the precipitation of solid phase (perovskite) below liquidus temperature, thereby, decreased the viscosity of high Ti-bearing blast furnace slag. For the effect of solid particles on slag viscosity, Einstein derived a simple model to estimate the viscosities of liquid with a low fraction of solid particles.23,24) He related the viscosity of the liquid-solid phase mixture to volume fraction of particles by Eq. (1).

\[ \eta = \eta_o \left(1 + \frac{5}{2} f \right)^{2.5} \] .......................... (1)

where \(\eta\) is the viscosity of the two phase mixture, \(\eta_o\) is the viscosity of pure liquid, \(f\) is the fraction of solid particles. Since the interactions between the solid particles are not considered, the equation can only be applied to the system with very low fraction of solid particles. For the present study, when the temperature was higher than liquidus temperature, there was only a very low fraction of solid particles (TiC), so it accorded with Einstein equation. However, as a result of very low fraction of solid particles, it had very small effect on viscosity of molten slag according to Eq. (1). The main reason for viscosity variation was B2O3 addition.

According to Wu’s experimental study,25) for a higher fraction of solid particle (below 15%), Einstein-Roscoe equation can be used to estimate as follows:

\[ \eta = \eta_o \left(1 - 1.35 f \right)^{-2.5} \] .......................... (2)

The power 2.5 was from Einstein’s Eq. (1), while 1.35 was optimized base on big number of experimental data. \(\eta_o\) is the viscosity of pure liquid. For the present study, volume fractions of perovskite were all lower than 7.7% which can be seen in Table 5. Therefore, the change of \(\eta\) for the present experiment can be in accordance with Einstein-Roscoe equation. It gave strong evidence for the change of viscosity with the change of solid phase at 1 610 K when different contents of B2O3 were added to the samples. From Eq. (2), it can be easily seen that, with the increase of \(f\), \(\eta\) increased sharply. That was why the viscosity of these slags for the present study increased sharply below the liquids temperature.

5. Conclusions

The influence of B2O3 on the viscosity of high Ti-bearing BF slag was studied under Ar atmosphere from hearth temperature of PANGANG’s BF. The results showed that the generation of small quantity of TiC was not primary cause for the increase of molten slag viscosity. The main reason for the increase of viscosity was precipitation of perovskite. The addition of adequate B2O3 can effectively decrease the viscosity of high Ti-bearing BF slag, consequently improve its fluidity. Some important findings were as follows:

(1) The existence of UPC can increase the viscosity of the slag and deteriorate its fluidity to some extent, and fortunately, B2O3 can counteract the negative factor and decrease the viscosity of the slag and improve its fluidity.

(2) At a low temperature, boron appeared with boron oxygen tetrahedron [BO]5−, which should have made the viscosity of molten slag increase. However, B2O3 was easy to form a eutectic which was even more powerful to decrease the viscosity of molten slag. On the whole, the viscosity of molten slag decreased at the temperature. At a high temperature, besides the effect of temperature on viscosity, some tetrahedron [BO]5− changed into triangle [BO]3− which would disintegrate the chains/molecules of molten slag and made the structure of molten matrix become loose, so the viscosity would further decreased.

(3) Liquidus temperature of the slags for present study was about 1 616 K. With the increase of B2O3 addition, volume fraction of liquid phase increased and volume fraction of perovskite decreased at 1 610 K. For slag with the existence of UPC, when the content of B2O3 increased from 0 to 4.1%, the solid fraction decreased from 7.7% to 1.6% at 1 610 K.

(4) When the temperature was below 1 610 K, the viscosity of all the slags increased sharply, still, the viscosity was lower for higher content of B2O3 at the same tempera-
ture. The precipitation of solid phase was the primary cause for the sharp increase of viscosity value.

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