Effect of Magnesium Oxide Content on Final Slag Fluidity of Blast Furnace

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Generally, decreasing the slag volume of the blast furnace operation can lead to a lower fuel ratio and higher productivity. For the high sinter ratio operation, one of effective ways to obtain a lower slag volume is to reduce the gangue content of the sinter. Basically, lowering the amount of serpentine in the sinter mix is a feasible way to produce suitable sinter with a lower gangue content. However, this method may result in a lower magnesium oxide content in the final slag that may affect its fluidity. Hence, the objective of this study was to evaluate the effect of MgO on the fluidity of blast furnace final slag. The liquidus temperature and viscosity of semi-synthetic slag were measured by using an optical softening temperature device and a viscometer, respectively, and the data were calculated to develop the iso-liquidus temperature and iso-viscosity diagrams. The experimental results indicated that the lower liquidus temperature and the better viscosity stability lay in the area of MgO=5.4 mass%, Al_2O_3=10-15 mass%, and CaO/SiO_2(B2)=1.2 for the range of composition studied. It was found that liquidus temperature decreased with decreasing MgO content and the viscosity of slag could be regarded as being independent of MgO content in the range of MgO=5-9 mass%, Al_2O_3=15 mass%, and B2=1.0-1.2 from several observations in the iso-fluidity diagrams of the blast furnace final slag. This study suggested that the MgO content could be lowered from current 6.5 mass% to 5.4 mass% in the conditions of Al_2O_3=15 mass%, and B2=1.2 under a stable blast furnace operation with a high thermal level, and this suggestion had been implemented in the present blast furnace operation.

1. INTRODUCTION

The blast furnace final slag is made from the meltdown liquid of sinter, lump, coke and flux at high temperature, and can be approximately considered a mixture of the four oxides, SiO_2, Al_2O_3, CaO, and MgO. There are four kinds of slags with distinct compositions produced at different regions inside the blast furnace via a series of reduced reactions. Primary slag, bosh slag, tuyere slag and final slag are respectively generated in the cohesive zone, dripping zone, raceway and hearth. As is well known, good tapping is primarily based on the fluidity of the final slag (low liquidus temperature, low viscosity, and wide fluidity). Generally, the major operating region of blast furnace slag for good fluidity in the quaternary system (SiO_2-Al_2O_3-CaO-MgO) liquidus diagram is the melilites phase (solid solutions of akermanite, $Ca_2MgSi_2O_7$, and gehlenite, $Ca_2Al_2SiO_7$). Generally, decreasing the slag volume of the blast furnace operation can obtain a lower fuel ratio and higher productivity. For the high sinter ratio operation, one effective way to reach the lower slag volume is to reduce the gangue content of sinter. Basically, lowering the amount of serpentine in the sinter mix is a feasible way to produce the qualified sinter with a lower gangue content. However, this method may result in a lower content of MgO in the final slag. POSCO showed that the permeability was not changed at the bosh zone when the MgO content was decreased from 6.2% to 4.1%, and good slag fluidity was obtained under the conditions of slag basicity (B2)=1.18 and MgO=5%. [1-3] NSC also indicated that when the MgO content decreased to 5.4 %, the blast furnace operation cost and slag volume was reduced. [4]

The average data of China Steel Corporation (CSC) BF operation for the final slag in 2007 are summarized in Table 1. It can be seen that the MgO content of the final slag ranged from 6.43% to 6.65%, the Al_2O_3 content was around 15%, B2 was controlled within 1.18 to 1.20, and the hot metal temperature (HMT) was around 1,500°C. [5] It is evident that the MgO content of the final slag at CSC is able to decrease when compared with POSCO. Therefore, the objective of this study was to evaluate the effect of MgO on the

Table 1   Average Data of MgO, Al₂O₃, B2 and HMT for CSC BF Final Slag in 2007

		1BF	2BF	3BF	4BF	Range
2007 Averages	MgO(%)	6.65	6.50	6.43	6.47	6.43-6.65
	Al₂O₃(%)	14.81	15.21	15.00	15.17	14.81-15.21
	B2(-)	1.18	1.19	1.20	1.20	1.18-1.20
	HMT(°C)	1504	1504	1497	1495	1495-1504

fluidity of the blast furnace final slag and find the appropriate level to which the MgO content can be reduced. A final slag fluidity database will be built for reference on burden preparation of blast furnace by using the experimental results and iso-fluidity diagrams.

2. EXPERIMENTAL METHOD

2.1 Experimental Apparatus

The measurements of the liquidus temperature and of the viscosity of the semi-synthetic slag were made by using an optical softening temperature device and a viscometer, respectively.

(1) Optical Softening Temperature Device

The schematic diagram of the experimental set up used for measuring the softening temperature of the slag by observing the deformation of the sample is shown in Fig. 1. A horizontal tube furnace that could be heated up to a maximum temperature of 1,700°C was used. Each end of the reaction tube was properly sealed by water-cooling metal caps to prevent air entering into the system, and closed by a quartz window allowing the CCD camera to follow the experiments visually. A thermocouple was inserted into the furnace through the quartz window, and the reaction tube was purged with Ar gas throughout the duration of

experiment. In this experiment, approximately 0.07 g of cylindrical slag sample (outside diameter: 3 mm, height: 3 mm) was placed on the MgO substrate kept in the ceramic reaction tube.

(2) Viscometer

A rotating cylindrical method was adopted to measure the viscosity of the molten slag. The apparatus is schematically shown in Fig. 2. A viscometer is connected to a graphite spindle through a graphite rod. The spindle consists of a bob and a shaft, of which the dimensions are also shown Fig. 2. The graphite crucible has a 50 mm internal diameter, 140 mm height, and 10 mm thickness of wall and base. The graphite crucible containing the slag sample (about 120 g of mixed powder) was placed in a given position of the heated furnace where the temperature distribution was uniform. The slag samples were kept molten for more than 2 hours, and the rotating spindle was then completely immersed into the molten samples. The holding time for reaching equilibrium state was more than 20 minutes at each experimental temperature. A metal flange was used to fill the gap between the ceramic reaction tube and the viscometer, and Ar gas was flowed into the reaction chamber at 0.4 L/min. The viscometer was calibrated by using Brookfield standard solutions with 0.5-49 poise at room temperature.
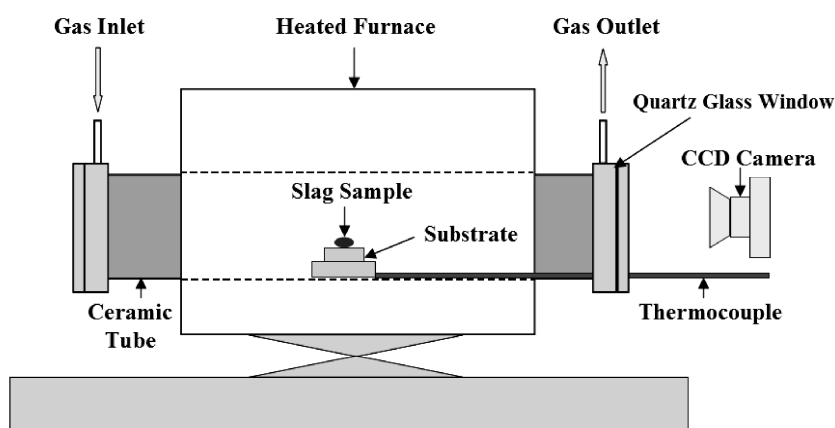

Fig. 1.   The schematic diagram of experimental apparatus for the measurement of the softening temperature.
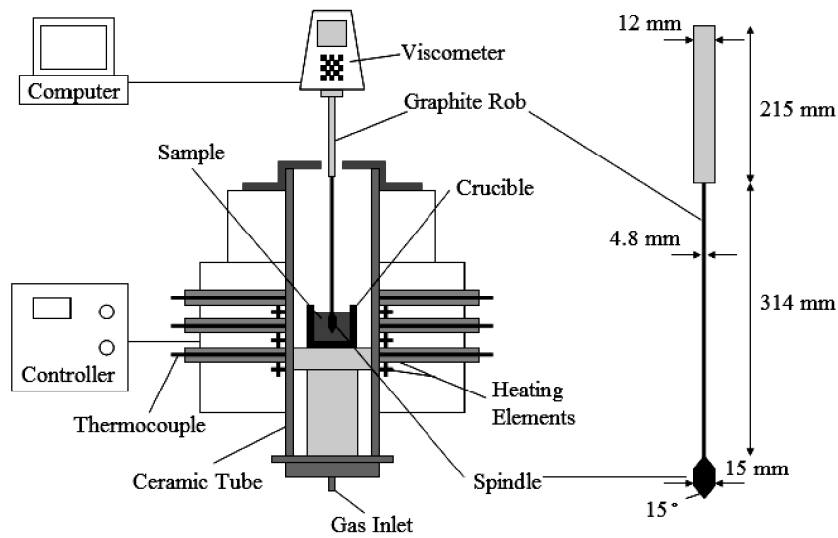
Fig. 2.   The schematic diagram of experimental apparatus for the viscosity measurement.

2.2 Experimental Procedure

In this experiment, the viscosity measurements of the semi-synthetic slag were made by the rotating cylinder method using a Brookfield digital viscometer, and the liquidus temperature was measured with an optical softening temperature device. The experimental approach for the fluidity measurement in this study is given in Fig. 3. At the beginning, the semi-synthetic slag samples were the water-quenched slag obtained from the blast furnace, and prepared with different MgO contents and B2 by adding pure oxide powers (reagent grade). In order to prepare a uniform slag,

110-120 g of mixed SiO_2-CaO-Al_2O_3-MgO slag was pre-melted in a graphite crucible under the atmosphere of Ar gas (0.4 L/min) at 1,500°C. Afterward, the melt was cooled to form solid (slag), and the solid milled into a fine powder. After the fine powder of uniform synthetic slags had been prepared, three kinds of measurements on the slag samples were conducted at the same time: (1) preparation of briquette samples, followed by heating the samples to measure the slag softening temperatures by observing their deformation as shown in Fig. 4; (2) analysis of the slag chemical compositions; (3) measuring the slag viscosity by using a viscometer at high temperature. Finally, the measured
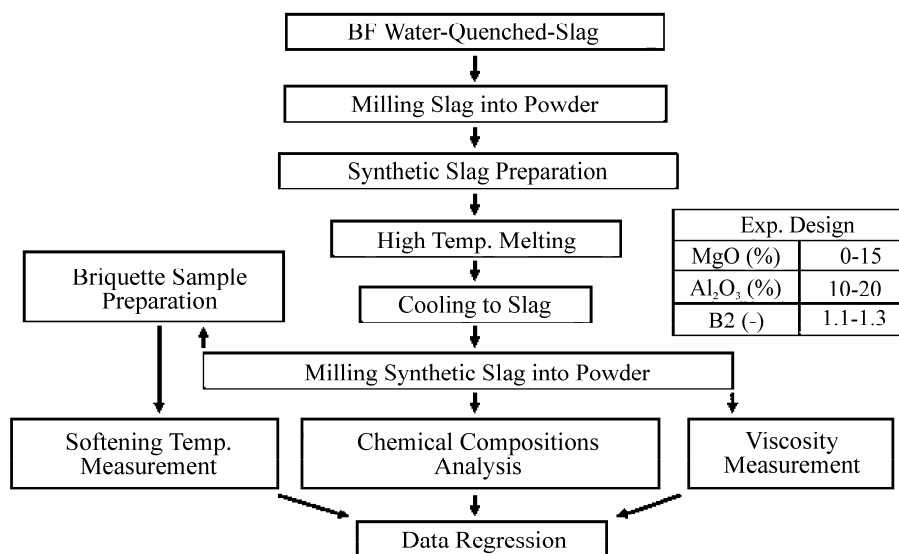

Fig. 3.   The experimental approach for fluidity measurement in this study.

(a) Original Form

(b) Deformation Temperature (DT)

(c) Liquidus Temperature (LT)
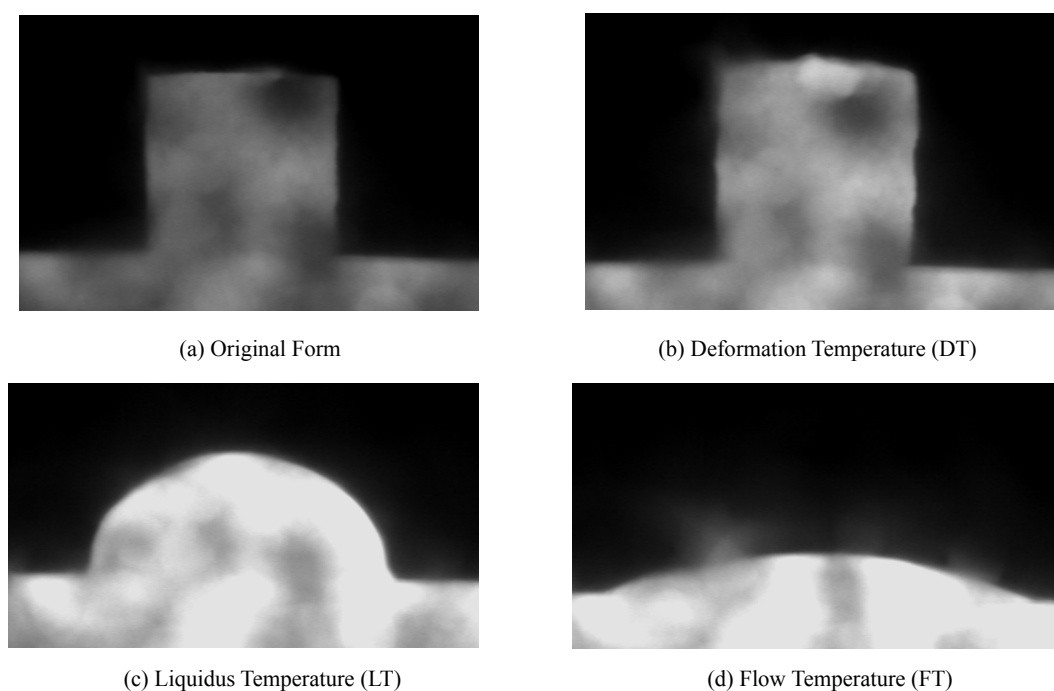
(d) Flow Temperature (FT)

Fig. 4.   The softening temperatures based on the deformation of the slag samples.

data for liquidus temperature and viscosity was made by the multiple regression method to get mathematic equations, and the iso-fluidity diagrams could be developed by combining the equation: $SiO_2 + CaO + Al_2O_3 + MgO = 100\%$.

The original form of a briquette sample is shown in Fig. 4(a). The form of the briquette sample as it starts deforming is given in Fig. 4(b); at this time, the temperature was defined as the deformation temperature. When the sample had been heated to a semi-sphere form, as shown in Fig. 4(c), was defined as the liquidus temperature. Finally, Fig. 4(d) shows the sample form spreading gradually with the increasing temperature, and this point was named flow temperature. In the experimental design, the MgO content ranged from 0% to 15% and B2 ranged from 1.1 to 1.3 in order to investigate the effect of MgO content on liquidus temperature and viscosity of slag. From the investigation, it was possible to obtain a precise regression for measured data.

3. RESULTS AND DISCUSSION

3.1 Softening Temperatures of Final Slag

(1) Experimental
Figure 5 indicates the variation of the softening temperatures measured by observing the deformation of the slag sample as a function of the MgO content (0-15 mass%) for each slag composition at a basicity of B2=1.2 and 15 mass% Al_2O_3. In this plot, there are

four different softening temperatures, comprising the flow, liquidus, sphere and deformation temperature from high to low temperature. The curves in Fig. 5 show that the softening temperatures increased gradually then decreased with increasing MgO content, and that the lower softening temperatures could be obtained in the range of MgO content from 2.4 to 5.7 mass%. Figure 6 shows the dependence of softening temperature on B2 at 5.4 mass% MgO and 15 mass% Al_2O_3,
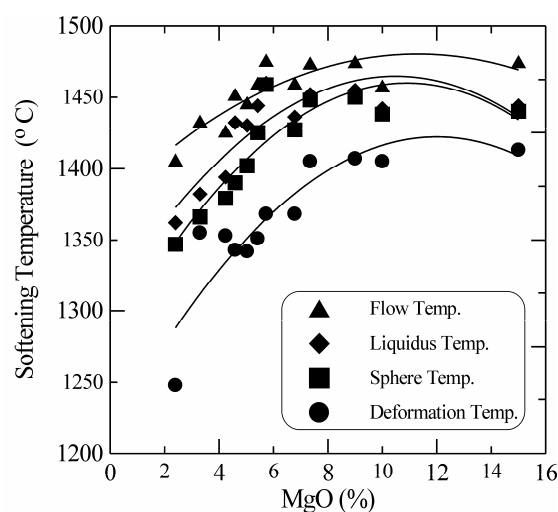

Fig. 5.   The variation of the softening temperatures as a function of the MgO content (0-15 mass%) at B2=1.2 and Al_2O_3=15 mass%.

where the softening temperatures increased gradually with the increasing B2. From the results in Fig. 6, the lower softening temperatures could be obtained in the range of B2 from 0.95 to 1.20.
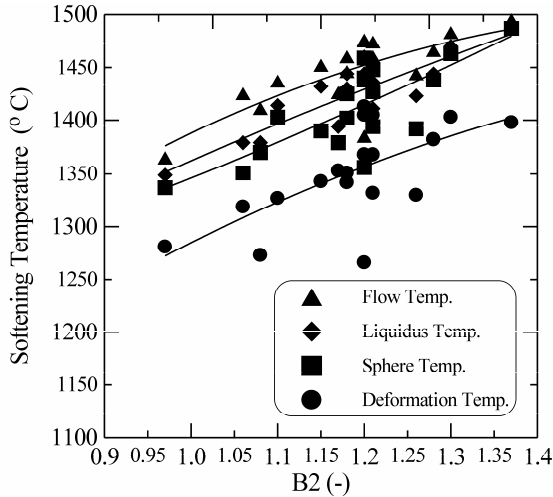

Fig. 6. The dependence of softening temperature on B2 at MgO=5.4 mass% and Al₂O₃=15 mass%.

(2) Multiple Regression

The data for both liquidus temperature (1,349-1,490°C) and composition of the slags (31.2-40.3 mass % SiO₂, 38.7-46 mass% CaO and 10.3-20.4 mass% Al₂O₃) were multiple-regressed to get an equation with R^2=0.95 as Eqn. (1) :

$$T_{liquidus} = aSiO_2^2 + bCaO^2 + cMgO^2 + dAl_2O_3^2 + eSiO_2 + fCaO + gMgO + hAl_2O_3 \; ....(1)$$

Then, the liquidus isotherms diagram could be obtained by using the combination of the normalized sum of four oxides with the formula as $SiO_2 + CaO + Al_2O_3 + MgO = 100\%$ (as shown in Fig. 7) at 15% mass% Al₂O₃. Each curve in Fig. 7 indicates the distribution of liquidus temperature as a function of slag composition. Based on the distribution of the different liquidus temperatures in this diagram, two distinct regions can be specified. The first region is specified for the slag where the liquidus temperature decreases with decreasing MgO content (when B2 < 1.3, MgO < 9 mass %). The second region is specified for the slag where the liquidus temperature is not affected by MgO content (when B2 > 1.3). From the result described in the distinct regions of the liquidus isotherms diagram, it is known that the liquidus temperature is favorable for the slag while decreasing the MgO content under a wide range of B2. In terms of the BF operation range (1.18 < B2 < 1.20, 6.43 mass% < MgO < 6.65 mass%) for CSC, the liquidus temperature ranges from 1,420 to

1,440°C and the slag composition is located in the first region, which means that a lower liquidus temperature could be obtained when the MgO content is reduced, according to the diagram.
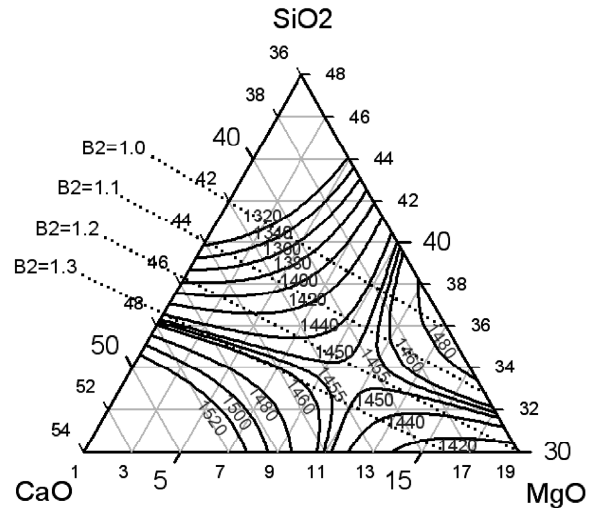

Fig. 7. The liquidus isotherms diagram for SiO₂-CaO-Al₂O₃-MgO semi-synthetic slag at Al₂O₃=15 mass%.

3.2 Viscosities of Final Slag

(1) Experimental

Figure 8 shows the effect of MgO content on the viscosities of SiO₂-CaO-Al₂O₃-MgO semi-synthetic slag as a function of temperature under the conditions of B2=1.2 and Al₂O₃=15 mass%, and these experimental results indicated that the slag viscosity increases with decreasing slag temperature. However, the distribution
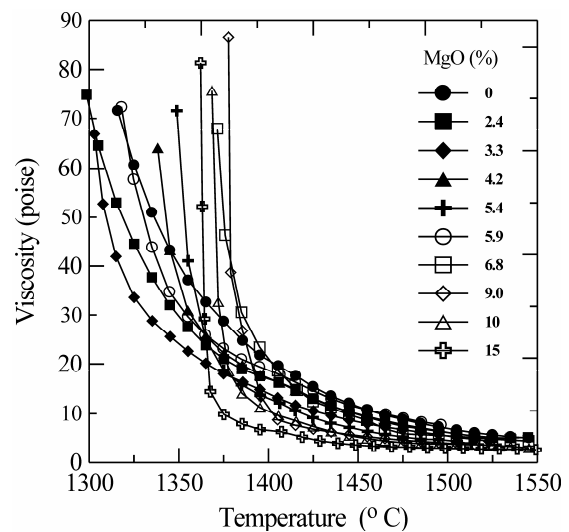

Fig. 8. The effect of MgO content on the viscosities of SiO₂-CaO-Al₂O₃-MgO semi-synthetic slag as a function of temperature at B2=1.2 and Al₂O₃=15 mass%.

of the curves in Fig. 8 is too complex to easily distinguish which conditions of the curves are good. For instance, from the curve which stands for the dependence of slag viscosity on the temperature at 15 mass% MgO, the viscosity is lower in the high slag temperature range but it becomes higher rapidly in the low slag temperature range; while the viscosity is lower in high temperature range but it increases slowly in the low temperature range for the dependence of slag viscosity on the temperature at 5.9 mass% MgO. Therefore, in order to determine the better viscosity stability, two criteria were set up. The first criterion for evaluating the stable viscosity is a lower melting temperature (<1,400°C). The melting temperature means the turning point of the curves in Fig. 8, and the results show that most melting temperatures are lower than 1,400°C except for the conditions of 6.8 and 9.0 mass% MgO. The second criterion was made to choose the lower viscosity from the lower melting temperatures for the MgO content studied in the first criterion. When the MgO content is lower than the BF operation range for CSC (MgO=6.43-6.65 mass%), it was found that the MgO content for the most stable viscosity in this work is 5.4 mass% by using the criteria. The tendency is observed in the temperature-viscosity curves of slag with different B2 values (1.1-1.3) under the conditions of MgO=5.4 mass% and Al$_2$O$_3$=15 mass% (as shown in Fig. 9). Figure 9 shows that a lower melting temperature for slag is observed at B2=1.2 by using the above criteria. Therefore, the more stable viscosity in this work is B2=1.2. It is also shown that the BF operation condition for CSC (B2=1.18-1.20) is located in the suitable range in this study. Actually, it was found that the appropriate MgO content for CSC still has room for

improvement based on the results given from Fig. 7 to Fig. 9.

(2) Multiple Regression

The data for viscosity (2.6-75 poise), composition of the slags (31.2-40.3 mass% SiO$_2$, 38.7-46 mass% CaO and 10.3-20.4 mass% Al$_2$O$_3$), and slag temperature were multiple-regressed to get an equation with R^2=0.95 as Eqn. (2):

$$\mu = a'SiO_2{}^2 + b'CaO^2 + c'MgO^2 + d'Al_2O_3{}^2 + e'SiO_2 + f'CaO + g'MgO + h'Al_2O^3 + i'T^2 + j'T \quad........(2)$$

The iso-viscosity distribution diagram can be obtained in the diagram (Al$_2$O$_3$=15 mass%, slag temperature = 1,500°C) by using the same calculation method as well as the isotherms diagram, as shown in Fig. 10. Each curve in Fig. 10 describes the distribution of viscosity related to the slag composition, and there are also two distinct regions which can be specified on the basis of the distribution of slag viscosity in the diagram. The first region is specified for the slag where viscosity is not affected by MgO contents (when B2=1.0-1.2, MgO =5-13 mass%). The second region is specified for the slag where the viscosity increases with decreasing MgO content (when B2 > 1.2, MgO < 9%). Therefore, there is no influence on the final viscosity by reducing MgO when B2=1.0-1.2. In terms of the BF operation range for CSC, the slag viscosity ranges from 5 to 6 poise and the slag composition approaches to the first region. However, the dominant factor for avoiding high viscosity is B2, and good slag viscosity can be still obtained as long as B2 is precisely controlled to about 1.20.

The iso-viscosity distribution diagrams (for 15 mass % Al$_2$O$_3$ at 1,450°C and 1,400°C, respectively) can be
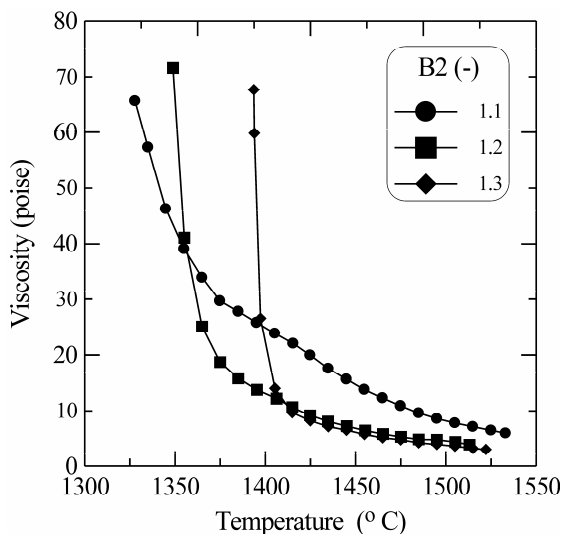

Fig. 9. The effect of B2 on the viscosities of SiO$_2$-CaO-Al$_2$O$_3$-MgO semi-synthetic slag as a function of temperature at MgO=5.4% and Al$_2$O$_3$=15 mass%.
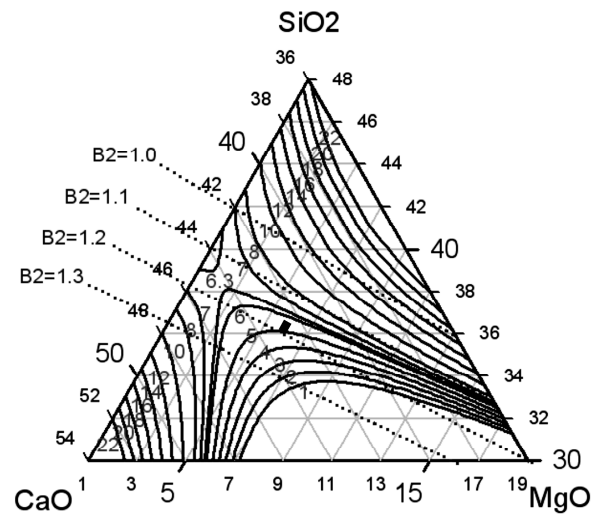

Fig. 10. The iso-viscosity diagram for SiO$_2$-CaO-Al$_2$O$_3$-MgO semi-synthetic slag at 1,500°C and Al$_2$O$_3$=15 mass%.

also developed in this study, as shown in Fig. 11 and Fig. 12 respectively. It was found that the distribution tendency of slag viscosity is similar to the distribution tendency for 1,500°C, the only difference being the lower the slag temperature the higher the slag viscosity at the same composition. The slag viscosities are respectively 8-9 poise and 16-17 poise for the BF operation range in CSC. In addition, Fig. 13 shows the diagram for slag isotherms as a function of compositions at a fixed viscosity (= 8 poise) by using the same calculation method as well as the iso-viscosity diagram, and the directions of the two arrowheads in this plot should be larger than 1,450°C to keep the slag viscosity

indicates that the slag temperature goes from low to high temperature. It is observed that slag temperature in 8 poise; however, it needs a much higher slag temperature while maintaining the better slag fluidity.
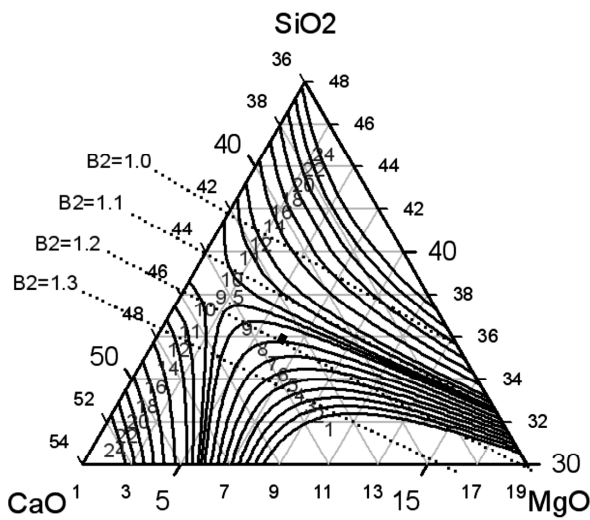

Fig. 13. The slag isotherms diagram for SiO_2-CaO-Al_2O_3-MgO semi-synthetic slag at fixed viscosity (=8 poise) and Al_2O_3=15 mass%.

3.3 Comparison of Liquidus Isotherms with Slag Isotherms

Comparing the results of Fig. 7 with Fig. 13, it is shown that the liquidus temperature will decrease when the MgO content is reduced from the BF operation range in CSC (6.43-6.65 mass%) to 5 mass%, and there is not much effect on the slag temperature (< 5°C). It is also in agreement with the description for the iso-viscosity diagrams at 1,400-1,500°C in Section 3.2 and the experimental results for liquidus temperature and viscosity in Sections 3.1-3.2. It follows from above-mentioned that the MgO content could be lowered from current 6.5 mass% to 5.4 mass% in the conditions of Al_2O_3=15 mass%, and B2=1.2 under a stable blast furnace operation with a high thermal level.

4. CONCLUSIONS

From above investigation, the following conclusions are obtained:

(1) The experimental results indicate that the lower liquidus temperature and the better viscosity stability lie in the area of MgO=5.4 mass%, Al_2O_3=10-15 mass%, and B2=1.2 for the range of composition studied.

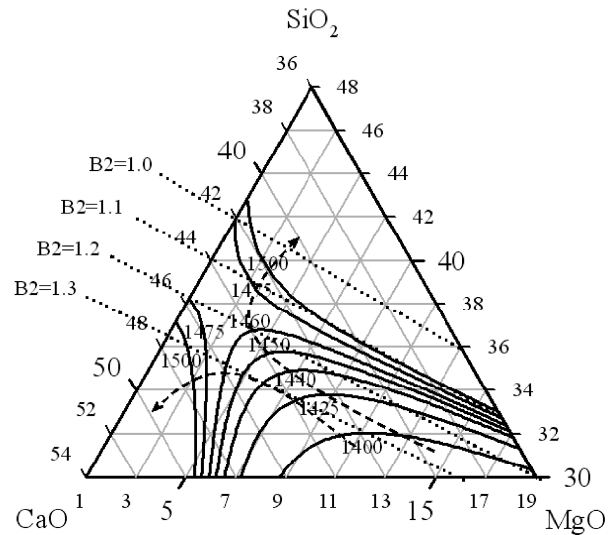(2) The observations in the liquidus isotherms and iso-viscosity diagrams of blast furnace final slag show

Fig. 11. The iso-viscosity diagram for SiO_2-CaO-Al_2O_3-MgO semi-synthetic slag at 1,450°C and Al_2O_3=15 mass%.
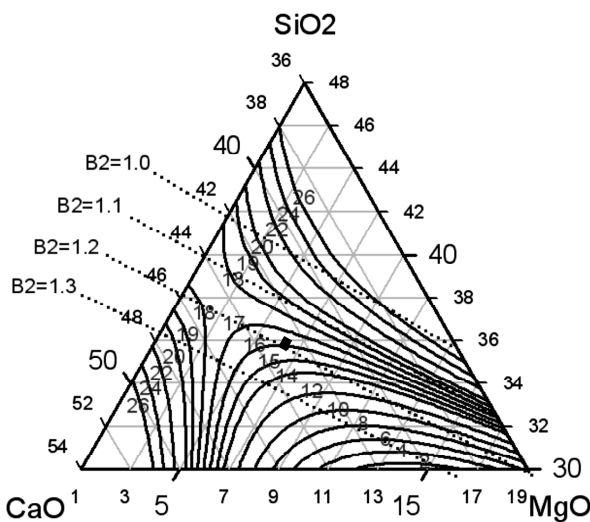
Fig. 12. The iso-viscosity diagram for SiO_2-CaO-Al_2O_3-MgO semi-synthetic slag at 1,400°Cand Al_2O_3=15 mass%.

that liquidus temperature decreases with decreasing MgO content and the viscosity of slag could be regarded as being independent of MgO content in the range of MgO=5-9 mass%, Al_2O_3=15 mass%, B2=1.0-1.2.

(3) This study suggestes that the MgO content could be lowered from the current 6.5 mass% to 5.4 mass% under the conditions of Al_2O_3=15 mass% and B2= 1.2 for a stable blast furnace operation with a high thermal level, and this suggestion has been implemented in the present blast furnace operation.

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