

Thermodynamic assessment of $\text{CaO-SiO}_2\text{-Al}_2\text{O}_3\text{-MgO-Cr}_2\text{O}_3\text{-MnO-Fe}_t\text{O}$ slags for refining chromium-containing steels

Sung-Koo Jo, Seon-Hyo Kim, Jeong-Sik Kim*, and Joung-Mo Lee**

School of Environmental Engineering, Pohang University of Science and Technology, Pohang, Kyungbuk, 790-784, Korea

*Iron & Steel Making Research Group, Technical Research Laboratories, POSCO, Kyungbuk, Korea

**Stainless Steel Department, Pohang Works, POSCO, Kyungbuk, Korea

Abstract

The slag system of $\text{CaO-SiO}_2\text{-Al}_2\text{O}_3\text{-MgO-Cr}_2\text{O}_3\text{-MnO-Fe}_t\text{O}$ relevant to refining chromium-containing steels such as bearing steel is thermodynamically assessed at 1873K. The activity coefficient of Fe_tO shows an initially rapid increment followed by a gradual reduction according to Cr_2O_3 content at a constant basicity, and decreases with increasing slag basicity. γ_{MnO} decreases abruptly with increasing Cr_2O_3 content and thereafter, maintains nearly constant. From the standpoint of inclusion control, the Cr_2O_3 presence in ladle refining slags is thermodynamically harmful in minimizing the inclusion level by inducing the increment of $\gamma_{\text{Fe}_t\text{O}}$ even though Cr_2O_3 exists extremely small, but beneficial in the aspect of diminishing Al reoxidation by decreasing γ_{MnO} . The thermodynamic equilibria of chromium and manganese are quantified in terms of Fe_tO and Cr_2O_3 contents as well as slag basicity with a multiple regression analysis. L_{Cr} and L_{Mn} are increased by the presence of Cr_2O_3 , indicating a low recovery efficiency of Cr and Mn in the treatment of ferroalloy addition. Whereas, the Cr_2O_3 -containing slags decrease L_{S} and shows a difficulty in controlling sulfur level in chromium-containing steels.

I. Introduction

There has been an increasing demand for high-grade steels of ultra cleanliness with minimum inclusion quantity. The reduction of oxide inclusions is performed by the flotation into the slag phase and prevention of Al reoxidation of steel in the ladle refining operations. The steel reoxidation by reducible oxides in slag such as Fe_tO and MnO induces the formation of fine inclusions, not easily floatable while the refining stage. Therefore, it is important to find out an optimum slag composition exhibiting minimum activity coefficients of reducible oxides causing the steel reoxidation for the production of ultra-clean steels.

During the production of high chromium-containing steels such as a bearing steel and stainless steel, the slag phase essentially contains chromium oxide to a certain degree. It is, thus, necessary to investigate activity behaviors of reducible oxides in the ladle slags containing chromium oxide for the minimization of steel reoxidation. However, the studies on the chromium oxide-containing slags have been mainly focused on the equilibria of $\text{Cr}^{2+}/\text{Cr}^{3+}$ and activity behavior of chromium oxide^[1-3]. There have not been reports on the effect of chromium oxide on the activity of Fe_tO and MnO in slag systems relevant to the ladle refining process. So, in this work, the thermodynamic equilibria between $\text{CaO-SiO}_2\text{-Al}_2\text{O}_3\text{-MgO-Cr}_2\text{O}_3\text{-MnO-Fe}_t\text{O}$ system and liquid iron have been carried out in an MgO crucible at 1873K. The activities of Fe_tO and MnO affecting the steel cleanliness will be discussed laying a stress on the effect of Cr_2O_3 content in slag.

The accurate yield prediction of ferroalloy addition is prerequisite in accommodating a narrow composition range of alloying elements allowable in high-grade steels and the high yield is also beneficial for cost reduction. In this aspect, the equilibrium chromium and manganese distribution ratios related to alloying yield of chromium and manganese in the ladle refining process will be investigated. As in the case of Fe_tO and MnO activity, the effect of Cr_2O_3 on the distribution ratios will be investigated emphatically. In addition, the sulfur distribution ratio between the employed slag system and liquid iron will be presented.

II. Experimental procedures

The equilibrium study between ladle slag and metal was carried out at 1873 K under Ar atmosphere in a LaCrO_3 resistance furnace equipped with a fused alumina tube of 50 mm ϕ and hot zone length of 5 mm. The tube was sealed in both ends with water-cooled brass lid. Argon gas was purified through, in order, H_2SO_4 , P_2O_5 , $\text{Mg}(\text{ClO}_4)_2$, a bed of Ti-granules at 620., $\text{Mg}(\text{ClO}_4)_2$ and then flown into a reaction tube. The master slags were prepared by premelting various mixtures of reagent grades CaCO_3 , SiO_2 , Al_2O_3 , and MgO in a graphite crucible, then crushed to a size below 60 mesh, and baked at 1100. for 24 h to remove any residual carbon.

The high-purity electrolytic iron ($[\% \text{O}]=0.0035$, $[\% \text{Al}]=0.0003$, $[\% \text{C}]=0.001$, $[\% \text{Si}]<0.001$) of 30 g and $\text{CaO-SiO}_2\text{-Al}_2\text{O}_3\text{-MgO}$ master slag of 8 g were initially melted using an MgO crucible. An appropriate amount of Fe-10% Si, Al and Fe-20% Mn alloy was added into the melt afterward. After equilibrating the melts for 5 hours, the crucible was pulled out of the furnace and rapidly quenched in a He gas stream, followed by water quenching. The schematic diagram of the experimental apparatus and the determination of equilibrium time are shown elsewhere in detail^[4].

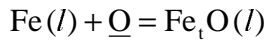
The quenched metal sample was sliced into a plate shape and its surface was peeled off. After ultrasonic cleaning with acetone and petroleum benzine, the metal sample was further sectioned into small pieces for chemical analyses. The silicon, aluminum, manganese and chromium in metal were analyzed with the help of an inductively coupled plasma emission spectrometry and oxygen by an inert-gas fusion infrared absorptiometry. The sulfur in metal and slag was determined by an oxygen-gas fusion infrared absorptiometry. The equilibrium slag composition was determined using X-ray fluorescence spectroscopy. ICP was also used to analyze slag samples containing a small amount of chromium ($< 0.05\%$).

III. Results and Discussion

The chemical compositions of metal and slag samples employed in this work are listed in Table I. The molar ratio of $(X_{\text{CaO}} + X_{\text{MgO}})/(X_{\text{SiO}_2} + X_{\text{Al}_2\text{O}_3})$ is used as a basicity index in the context unless specified in other way. Slag compositions with low contents of Cr_2O_3 , Fe_tO and MnO were chosen for aiming the ladle slag for refining chromium-containing steels.

Chromium in slag are generally represented by valencies of Cr^{2+} and Cr^{3+} at the steelmaking temperature and low oxygen potential. However, the proportion of chromium present in divalent state is markedly decreased by increasing $(X_{\text{CaO}} + X_{\text{MgO}})/X_{\text{SiO}_2}$ ratio^[5], less than 0.1 when the ratio is greater than ~ 3 . Therefore, in this work, it is assumed that chromium exists as a form of trivalent state in the slag.

The activity coefficient of Fe_tO can be calculated using the equilibrium constant of following reaction :



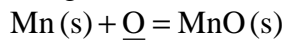
$$\Delta G_1^\circ = -116,100 + 48.79T \quad \text{J/mol}^{[6]} \quad (1)$$

$$K_1 = a_{\text{Fe}_t\text{O}}/a_{\text{O}} = \gamma_{\text{Fe}_t\text{O}} X_{\text{Fe}_t\text{O}}/f_{\text{O}}[\% \text{O}] \quad (2)$$

where the activity of total iron oxide in slag is referred with respect to pure liquid standard state and the activity of oxygen in metal is determined relative to 1 wt pct standard state. The values of $\gamma_{\text{Fe}_t\text{O}}$ can be obtained from equation (2) by using the experimental results in Table I as well as the respective interaction parameters in Table II^[7-8].

Figure 1 shows an effect of Cr_2O_3 content on activity coefficient of Fe_tO at various basicities. The value of $\gamma_{\text{Fe}_t\text{O}}$ shows an initially rapid increment with increasing Cr_2O_3 content and thereafter maintains constant before starting to decrease gradually at higher Cr_2O_3 with larger basicity. Fe_tO content does not affect its activity coefficient up to $X_{\text{Fe}_t\text{O}} = \sim 0.03$ in $\text{CaO-SiO}_2\text{-Al}_2\text{O}_3$ slag system as shown in Figure 2^[9]. It was, thus, considered that $\gamma_{\text{Fe}_t\text{O}}$ is not affected by Fe_tO content within a Henrian range of Fe_tO content. In this work, Fe_tO increases along with Cr_2O_3 as the oxygen content in metal increases. Over the initial range of Fe_tO content, the increment of $\gamma_{\text{Fe}_t\text{O}}$ is affected by the increase of Cr_2O_3 content. $\gamma_{\text{Fe}_t\text{O}}$ retains constant and even decreases beyond Henrian range, where Fe_tO content starts to affect its self-interaction parameters. From the viewpoint of minimizing inclusions through Al reoxidation in steel, the presence of Cr_2O_3 in slag is thermodynamically harmful even though its content is small. It is also shown that $\gamma_{\text{Fe}_t\text{O}}$ significantly decreases with increasing slag basicity at a fixed Cr_2O_3 content.

Manganese deoxidation equilibrium can be expressed as follows :



$$\Delta G_3^\circ = -288,100 + 128.37T \quad \text{J/mol}^{[10]} \quad (3)$$

$$K_3 = a_{\text{MnO}}/a_{\text{O}} = \gamma_{\text{MnO}} X_{\text{MnO}}/f_{\text{O}}[\% \text{O}] \quad (4)$$

where the activity of MnO is referred with respect to solid standard state. The values of γ_{MnO} can be also obtained likewise $\gamma_{\text{Fe}_t\text{O}}$.

The effect of Cr_2O_3 content on γ_{MnO} at a constant basicity is shown in Figure 3. In contrary to the case of $\gamma_{\text{Fe}_t\text{O}}$, the value of γ_{MnO} decreases rapidly with increasing Cr_2O_3 content and, then, becomes almost constant. MnO is considered to show a wider Henrian range up to ~ 0.1 mole fraction than Fe_tO as shown in Figure 4. Over the concentration range of MnO ($X_{\text{MnO}} <$

0.015) in the present work, γ_{MnO} could be regarded as not being affected by MnO content. From the above result, it can be inferred that Al reoxidation of steel by MnO is suppressed to some degree by the presence of Cr_2O_3 in slag. On the contrary, Cr_2O_3 can activate the steel reoxidation phenomena by Fe_tO as discussed in Figure 1. γ_{MnO} decreases slightly with increasing slag basicity at a fixed Cr_2O_3 content. Therefore, for the effective prevention of Al reoxidation by the ladle slags containing Cr_2O_3 , the contents of reducible slag components related to the steel reoxidation such as Fe_tO and MnO should be compromised simultaneously, not considered independently.

Meanwhile, the equilibrium of chromium between slag and liquid iron can be represented as the following reaction :



$$K_5 = \frac{a_{\text{Fe}_t\text{O}} a_{\text{Cr}}^{2/3}}{a_{\text{CrO}_{1.5}}^{2/3}} = \alpha \frac{\gamma_{\text{Fe}_t\text{O}} (\% \text{Fe}_t\text{O}) f_{\text{Cr}}^{2/3} [\% \text{Cr}]^{2/3}}{\gamma_{\text{CrO}_{1.5}}^{2/3} (\% \text{CrO}_{1.5})^{2/3}} \quad (6)$$

where α is a conversion parameter from mole fraction of Fe_tO and $\text{CrO}_{1.5}$ to mass % and retains almost constant irrespective of slag compositions. f_{Cr} is nearly constant because chromium in iron displays a Henrian behavior over the concentration range considered. From equation (6), the equilibrium chromium distribution ratio, $L_{\text{Cr}} (= (\% \text{CrO}_{1.5})/[\% \text{Cr}])$ can be written as follows :

$$\log L_{\text{Cr}} = 3/2 \log a_{\text{Fe}_t\text{O}} - \log \gamma_{\text{CrO}_{1.5}} + \log(\alpha f_{\text{Cr}}/K_5) \quad (7)$$

L_{Cr} is plotted against $a_{\text{Fe}_t\text{O}}$ in Figure 5, which exhibits a relatively good linearization according to the reaction (5) with a slope of 3/2. The practical data after RH treatment of bearing steel in POSCO^[11] are inserted in Figure 5, which are located above those of present work. It could be explained by the non-equilibrium attained locally for Cr/ $\text{CrO}_{1.5}$ reaction during the RH process, even though the Fe/ Fe_tO equilibrium is attained as will be shown later in Figure 9. It might be thermodynamically possible to recover further more chromium from the slag. In order to quantify the effect of slag compositions, L_{Cr} is empirically formulated in terms of $(\% \text{Fe}_t\text{O})$, $(\% \text{Cr}_2\text{O}_3)$, $(\% \text{MnO})$ and basicity using a multiple regression analysis. For a convenient comparison of $(\% \text{Cr}_2\text{O}_3)$ and basicity effects against $(\% \text{Fe}_t\text{O})$, the regression was performed with the unit weight factor for $\log(\% \text{Fe}_t\text{O})$ term. It was assumed that MnO ($< 1.5\%$) has a negligible effect on the activity behavior of other slag components. The resulting regression relation is formulated as shown in Figure 6.

$$\log L_{\text{Cr}} = \log(\% \text{Fe}_t\text{O}) + 0.45 \log(\% \text{Cr}_2\text{O}_3) - 0.054B - 0.30 \quad (8)$$

The basicity seems to be not an important parameter in determining L_{Cr} . The regression equation could be reasonably applied to the prediction of L_{Cr} between the ladle refining slag containing Cr_2O_3 ($< 4\%$), Fe_tO ($< 4.5\%$) and MnO ($< 1.5\%$) and liquid iron containing Cr ($< 1.5\%$) such as a bearing steel.

The slag/metal equilibrium of manganese is attained according to the following reaction :



$$K_9 = \frac{a_{\text{Fe}_t\text{O}} a_{\text{Mn}}}{a_{\text{MnO}}} = \beta \frac{\gamma_{\text{Fe}_t\text{O}} (\% \text{Fe}_t\text{O}) f_{\text{Mn}} [\% \text{Mn}]}{\gamma_{\text{MnO}} (\% \text{MnO})} \quad (10)$$

where β represents a conversion parameter likewise α . The equilibrium manganese distribution ratio, $_{\text{Mn}} (= (\% \text{MnO})/[\% \text{Mn}])$ is expressed as the following equation.

$$\log L_{\text{Mn}} = \log a_{\text{Fe}_t\text{O}} - \log \gamma_{\text{MnO}} + \log(\beta f_{\text{Mn}}/K_9) \quad (11)$$

The linearization tendency of $\log _{\text{Mn}}$ as a function $\log a_{\text{Fe}_t\text{O}}$ according to the reaction (9) is shown in Figure 7. $_{\text{Mn}}$ is regressed in terms of $(\% \text{Fe}_t\text{O})$, $(\% \text{Cr}_2\text{O}_3)$ and basicity with the unit factor for $\log(\% \text{Fe}_t\text{O})$ term.

$$\log L_{\text{Mn}} = \log(\% \text{Fe}_t\text{O}) + 0.34 \log(\% \text{Cr}_2\text{O}_3) - 0.10B + 0.86 \quad (12)$$

The basicity seems to have little effect on L_{Mn} similarly as in the case of L_{Cr} over the basicity considered in this work. The empirical relation (12) indicates that Cr_2O_3 can increase L_{Mn} and, thus, show a low alloying yield of manganese at constant Fe_tO content and slag basicity.

The equilibrium sulfur distribution between slag and liquid iron expressed by the following reaction is also discussed.



$$\log L_{\text{S}} = -\log_{\text{Fe}_t\text{O}} + \log_{\text{O}^{2-}} + \log(\delta f_{\text{S}}/K_{13} \gamma_{\text{S}^{2-}}) \quad (14)$$

δ is a nearly constant parameter irrespective of slag compositions likewise α , and $\gamma_{\text{S}^{2-}}$ is almost constant because of its Henrian behavior in slag. The equilibrium sulfur distribution ratio is plotted against Fe_tO in Figure 9 showing a validity of the theoretical slope of -1 at the fixed basicity according to the reaction (13). L_{S} increases with increasing basicity at the fixed Fe_tO unlikely as the case of L_{Cr} and L_{Mn} . The POSCO plant data is well consistent with the present equilibrium data, which means the practical operation attains nearly an equilibrium of sulfur reaction between slag and metal – i.e., the attainment of $\text{Fe}/\text{Fe}_t\text{O}$ equilibrium in the RH process. In terms of $(\% \text{Fe}_t\text{O})$, $(\% \text{Cr}_2\text{O}_3)$ and basicity, the experimentally observed L_{S} values are regressed with the unit weight factor for $\log(\% \text{Fe}_t\text{O})$ term.

$$\log L_{\text{S}} = -\log(\% \text{Fe}_t\text{O}) - 0.22 \log(\% \text{Cr}_2\text{O}_3) + 0.67B - 0.63 \quad (15)$$

In contrast to the case of L_{Cr} and L_{Mn} , slag basicity has a considerable effect on the equilibrium distribution ratio. From equation (15), it is considered that the sulfur distribution ratio is decreased by the presence of Cr_2O_3 in slag, which turns out to be unfavorable for the reduction of sulfur content in steel.

IV. Conclusions

The equilibrium study of ladle refining slag system containing Cr_2O_3 ($< 4\%$) has been performed to investigate the chromium and manganese distribution ratios related to the recovery efficiency as well as the activity coefficient of Fe_tO and MnO in the aspect of steel reoxidation by reducible oxides.

The activity coefficient of Fe_tO increases rapidly and thereafter, decreases gradually with increasing Cr_2O_3 content at a constant basicity. With increasing slag basicity, $\gamma_{\text{Fe}_t\text{O}}$ decreases at a constant Cr_2O_3 content. On the other hand, γ_{MnO} decreases abruptly with increasing Cr_2O_3 and maintains nearly constant at high Cr_2O_3 content. The simultaneous consideration of Fe_tO and MnO for their optimized compositions under the existence of some Cr_2O_3 content is needed for the effective prevention of steel reoxidation by the reducible components, because of the opposite behaviors of their activity coefficients with respect to Cr_2O_3 .

The equilibrium correlations of chromium, manganese and sulfur distribution ratios with respect to the relevant slag components were empirically determined using a multiple regression analysis, which could predicted reasonably the equilibrium distribution ratios of Cr, Mn and S between the ladle refining slag containing Cr_2O_3 ($< 4\%$), Fe_tO ($< 4.5\%$) and MnO ($< 1.5\%$) and liquid iron containing Cr ($< 1.5\%$) such as a bearing steel.

$$\log L_{\text{Cr}} = \log(\% \text{Fe}_t\text{O}) + 0.45 \log(\% \text{Cr}_2\text{O}_3) - 0.054B - 0.30$$

$$\log L_{\text{Mn}} = \log(\% \text{Fe}_t\text{O}) + 0.34 \log(\% \text{Cr}_2\text{O}_3) - 0.10B + 0.86$$

$$\log L_{\text{S}} = -\log(\% \text{Fe}_t\text{O}) - 0.22 \log(\% \text{Cr}_2\text{O}_3) + 0.67B - 0.63$$

The alloying yields of Cr and Mn can be diminished with the increasing Cr_2O_3 content. The minimization of sulfur in steel may not be easily achieved in case of refining chromium-containing steels.

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Figure 1. The effect of Cr_2O_3 on the activity coefficient of Fe_2O_3

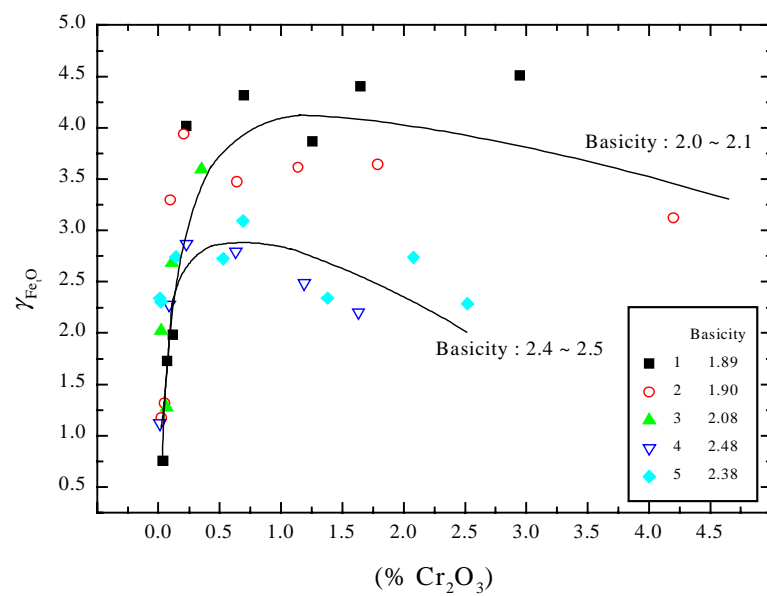
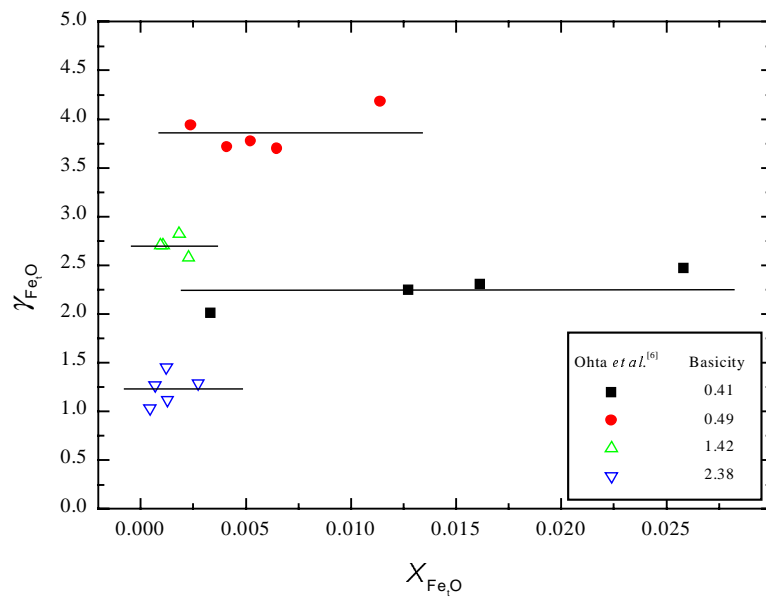


Figure 2. The activity coefficient of Fe_tO for $\text{CaO-SiO}_2\text{-Al}_2\text{O}_3$ slags (after Ohta *et al.*^[6])



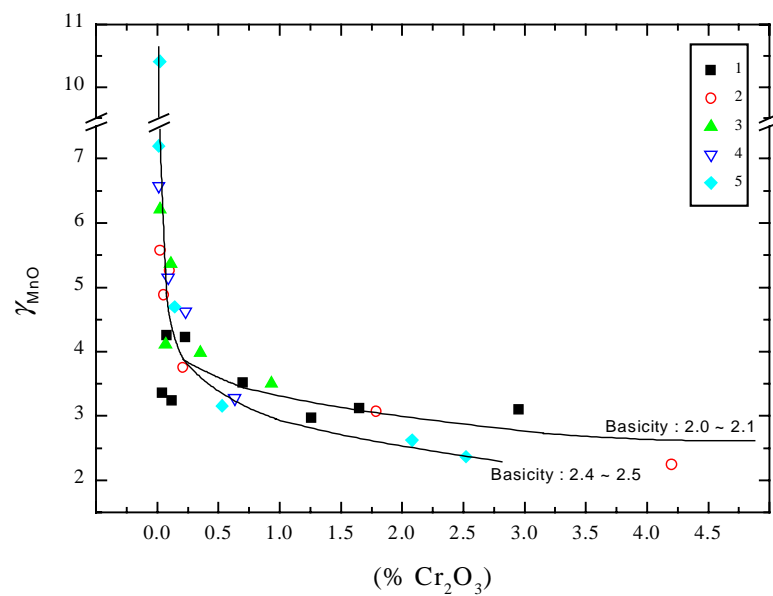


Figure 3. The effect of Cr_2O_3 on the activity coefficient of MnO

Figure 4. The activity coefficient of MnO for CaO-SiO₂-Al₂O₃ slags (after Ohta *et al.*^[6])

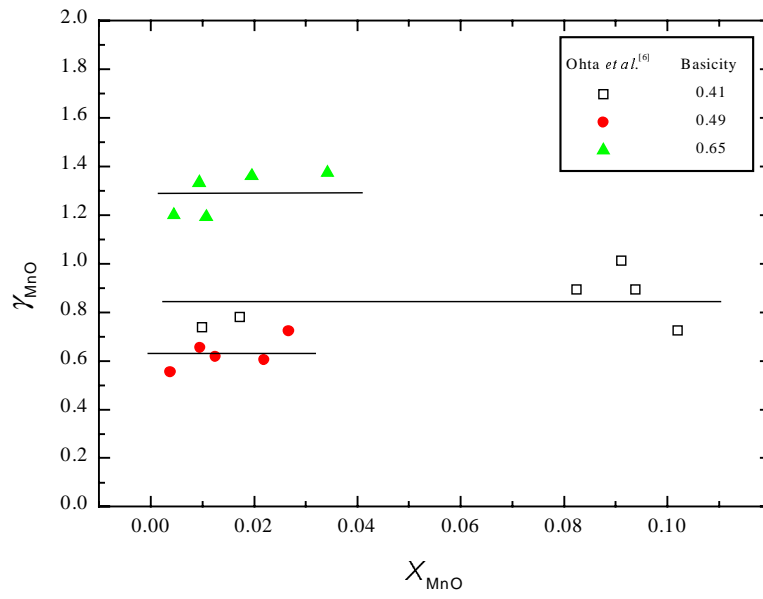


Figure 5. Chromium distribution ratio, L_{Cr} , plotted against the activity of Fe_2O_3

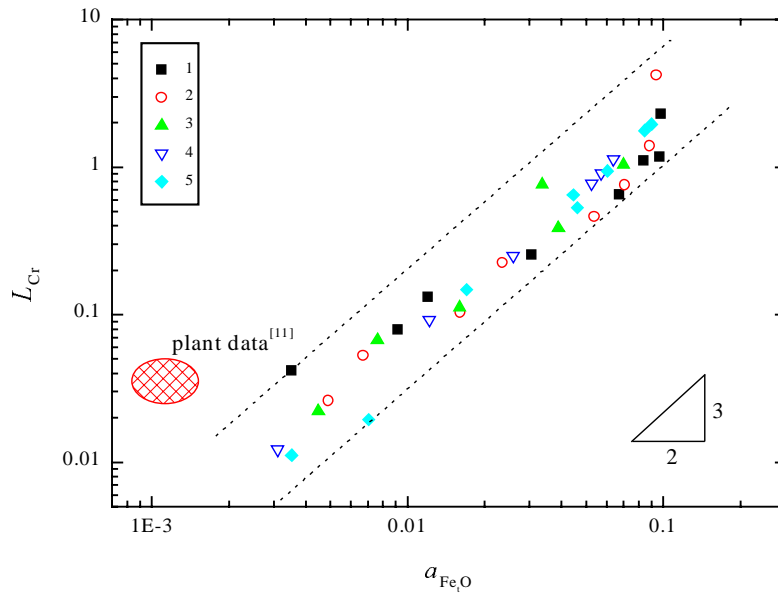


Figure 6. Comparison of the calculated and observed chromium distribution ratio, L_{Cr}

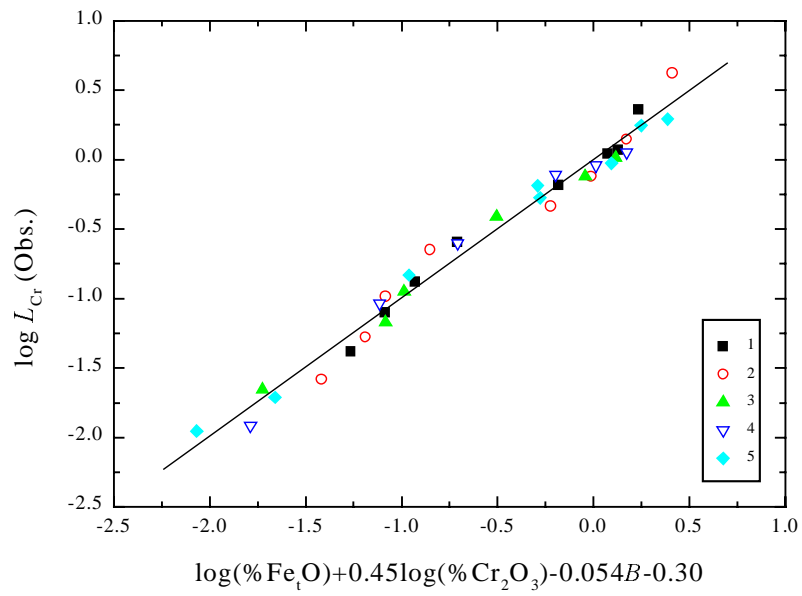


Figure 7. Manganese distribution ratio, L_{Mn} , plotted against the activity of Fe_iO

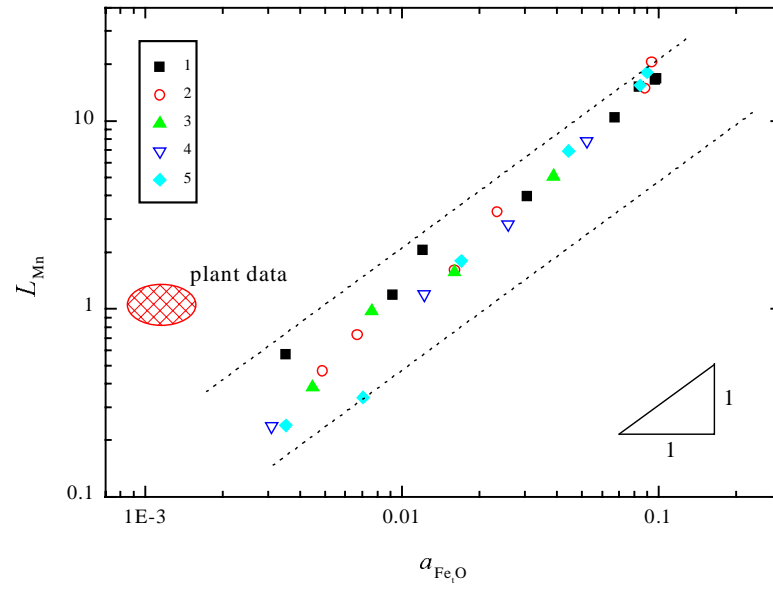


Figure 8. Comparison of the calculated and observed manganese distribution ratio, L_{Mn}

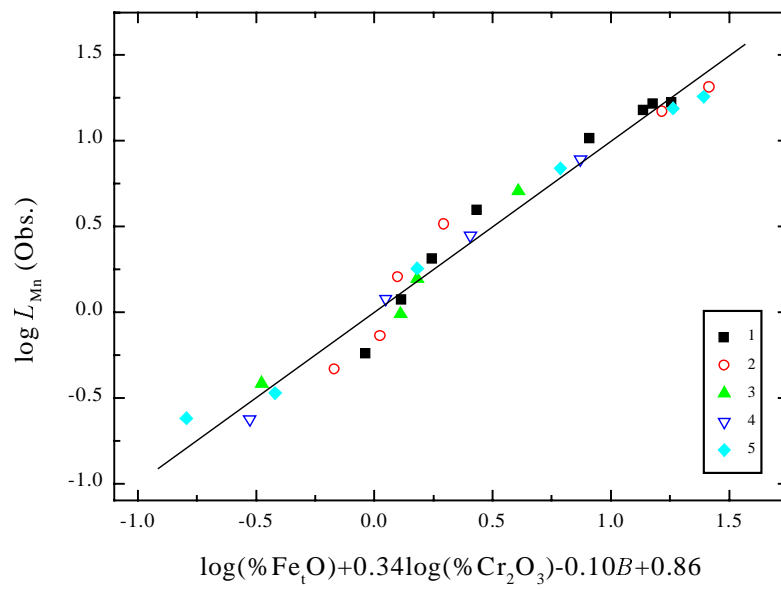


Figure 9. Sulfur distribution ratio, L_S , plotted against the activity of Fe_tO

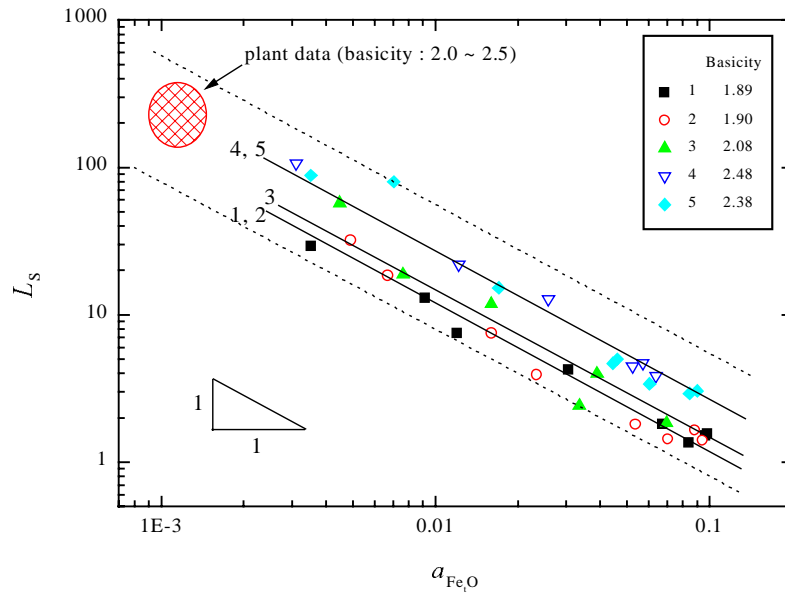


Figure 10. Comparison of the calculated and observed sulfur distribution ratio, L_S

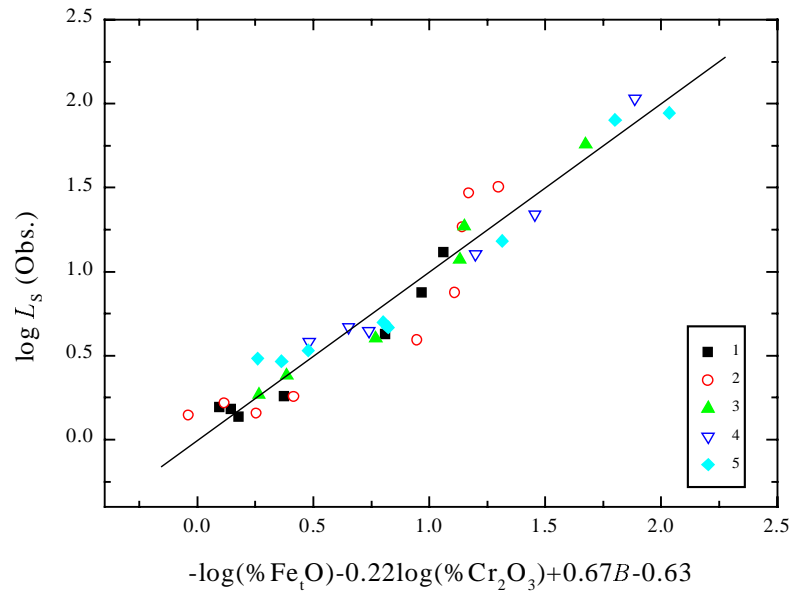


Table I. The Equilibrium Compositions of Slag and Metal at 1873K

		Slag (Mass Pct)								Metal (Mass Pct)						
		*Basicity	(CaO)	(SiO ₂)	(Al ₂ O ₃)	(MgO)	(Cr ₂ O ₃)	(MnO)	(Fe ₂ O)	(S)	[Si]	[Al]	[Cr]	[Mn]	[O]	[S]
No. 1	1.89															
1-1		36.90	23.15	17.55	15.48	2.95	1.49	2.65	0.056	0.0021	0.0041	1.282	0.089	0.024	0.036	
1-2		37.82	23.47	17.70	15.31	1.65	1.50	2.69	0.053	0.0024	0.0045	1.409	0.091	0.024	0.035	
1-3		38.60	23.86	17.50	15.37	1.26	1.50	2.69	0.049	0.0022	0.0047	1.144	0.099	0.020	0.036	
1-4		38.97	24.72	17.24	16.00	0.70	1.38	1.95	0.058	0.0024	0.0033	1.071	0.133	0.016	0.032	
1-5		40.55	24.92	17.55	16.15	0.23	0.95	0.96	0.093	0.0022	0.00080	0.906	0.240	0.0070	0.022	
1-6		40.43	25.47	17.61	16.91	0.12	0.63	0.77	0.12	0.0088	0.0010	0.913	0.308	0.0028	0.016	
1-7		39.84	25.75	17.44	17.11	0.074	0.43	0.67	0.13	0.0397	0.0077	0.932	0.364	0.0023	0.010	
1-8		39.90	25.87	17.72	17.21	0.039	0.24	0.59	0.17	0.2158	0.0022	0.938	0.418	0.0009	0.0058	
No. 2	1.90															
2-1		33.48	16.27	24.02	14.37	4.20	1.50	3.41	0.049	0.0022	0.0070	1.001	0.073	0.023	0.035	
2-2		36.49	17.22	25.98	14.87	1.79	1.47	2.88	0.056	0.0020	0.00088	1.281	0.099	0.021	0.034	
2-3		37.35	17.41	26.50	14.87	1.14	1.49	2.31	0.053	0.0027	0.0018	1.505	0.268	0.017	0.037	
2-4		37.91	17.59	27.01	15.36	0.64	1.32	1.85	0.063	0.0026	0.0010	1.385	0.313	0.013	0.035	
2-5		38.90	17.98	27.42	16.00	0.21	0.88	0.72	0.090	0.0037	0.00085	0.935	0.269	0.0054	0.023	
2-6		39.20	18.76	26.34	16.13	0.10	0.55	0.59	0.12	0.0081	0.00082	0.965	0.343	0.0037	0.016	
2-7		39.45	19.21	26.20	16.14	0.052	0.30	0.62	0.14	0.0510	0.0015	0.985	0.413	0.0016	0.0076	
2-8		38.95	18.95	26.67	16.56	0.025	0.20	0.51	0.15	0.1493	0.0027	0.958	0.430	0.0012	0.0047	
No. 3	2.08															
3-1		41.70	16.74	23.84	12.58	1.49	1.46	2.80	0.061	0.0027	0.0197	1.442	0.269	0.020	0.033	
3-2		42.74	17.02	24.15	12.85	0.93	1.40	2.42	0.070	0.0087	0.0675	1.224	0.283	0.014	0.029	
3-3		44.43	17.74	23.59	12.82	0.35	1.07	1.30	0.092	0.0037	0.0138	0.904	0.211	0.010	0.023	
3-4		44.78	18.44	23.51	13.35	0.11	0.54	0.72	0.13	0.0041	0.0071	0.982	0.345	0.0039	0.011	
3-5		43.93	18.99	23.34	13.59	0.066	0.38	0.72	0.14	0.0135	0.0171	0.978	0.391	0.0021	0.0075	
3-6		44.36	19.45	23.69	13.98	0.022	0.17	0.27	0.16	0.0690	0.0064	0.995	0.444	0.0012	0.0028	
No. 4	2.48															
4-1		44.35	5.93	33.24	10.80	1.63	1.40	3.25	0.088	0.0020	0.0067	1.453	0.273	0.016	0.023	
4-2		45.88	6.18	32.98	11.01	1.19	1.36	2.61	0.098	0.0027	0.0060	1.312	0.285	0.014	0.021	
4-3		44.56	5.93	34.69	11.60	0.63	1.21	2.12	0.093	0.0038	0.0046	0.815	0.155	0.012	0.021	
4-4		47.83	7.02	33.48	11.33	0.23	0.77	1.04	0.14	0.0034	0.0042	0.920	0.275	0.0061	0.011	
4-5		47.29	7.88	33.80	11.79	0.088	0.44	0.62	0.14	0.0033	0.0048	0.957	0.370	0.0029	0.0064	
4-6		46.81	8.36	33.98	11.81	0.012	0.11	0.32	0.16	0.0420	0.0070	0.987	0.464	0.0010	0.0015	
No. 5	2.38															
5-1		40.80	4.37	35.03	11.10	2.52	1.43	4.32	0.079	0.0021	0.0044	1.290	0.079	0.022	0.026	
5-2		41.18	4.45	36.02	11.42	2.08	1.39	3.41	0.079	0.0021	0.0057	1.179	0.090	0.020	0.027	
5-3		42.76	4.42	37.16	11.38	1.38	1.37	2.88	0.085	0.0030	0.0034	1.463	0.285	0.015	0.025	
5-4		44.35	4.64	37.54	11.58	0.69	1.19	1.68	0.11	0.0027	0.00085	1.298	0.330	0.011	0.022	
5-5		44.80	4.54	37.29	11.84	0.53	1.16	1.85	0.098	0.0034	0.0107	0.818	0.168	0.011	0.021	
5-6		45.14	5.39	38.04	12.31	0.14	0.59	0.71	0.14	0.0033	0.00046	0.948	0.328	0.0039	0.0092	
5-7		45.87	5.94	37.79	12.13	0.019	0.15	0.35	0.16	0.0263	0.0028	0.977	0.445	0.0018	0.0020	
5-8		42.03	5.72	40.46	13.15	0.011	0.11	0.17	0.15	0.1206	0.0075	0.987	0.458	0.0011	0.0017	

*Basicity : $(X_{\text{CaO}}+X_{\text{MgO}})/(X_{\text{SiO}_2}+X_{\text{Al}_2\text{O}_3})$

Table II. The Interaction Parameters Used in This Work^[4]

$i \quad e_i^j \quad j$ $r_i^j \quad (r_i^{ij})$	Si	Al	Cr	Mn	O	S
Si	0.11 -0.0021	0.058 -	-0.0003 -	0.002 -	-0.23 -	0.056 -
Al	0.056 -0.0006	0.045 -0.001	- -	- -	-6.9 ^[5] 7.6(9.05)	0.03 -
Cr	-0.0043 -	- -	-0.0003 0	- -	-0.14 -	-0.02 -
Mn	0 0	- -	- -	0 0	-0.083 -	-0.048 -
O	-0.131 0	-4.09 ^[5] 2.67(9.05)	-0.04 -	-0.021 0	-0.2 -	-0.133 0
S	0.063 0.0017	0.035 0.0009	-0.011 0	-0.026 0	-0.27 -	-0.028 -0.0009