ASSESSMENT OF VISCOSITY OF SLAGS IN FERROCHROMIUM PROCESS

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ABSTRACT

Viscosity of the slag is one of the central parameters when producing FeCr in submerged arc furnaces. It contributes to smelting behaviour and reduction kinetics of chromite ore as well as to the Cr recovery by influencing the separation of dispersed metal droplets from the slag. A typical FeCr process slag contains 5-10 pct chromium oxides, CrO and $CrO_{1.5}$.

The neural network computation was applied to the evaluation of viscosity for slags containing chromium oxides, and the prediction of viscosity in FeCr process slag was conducted. The main results in this estimation were that the chromium oxides in FeCr process slag lower its viscosity, and that the effect of CrO on the viscosity decrease is greater than that of $CrO_{1.5}$.

1. INTRODUCTION

Production of ferrochromium is mostly conducted in submerged electric arc furnaces. A large amount of slag is produced from gangue material associated with the ores and fluxes added to the furnace burden. Viscosity is one of the central properties of molten slag having an influence on the phenomena in the furnace, such as smelting and reduction of chromite, and settling of metal droplets from the slag [1]. The concentration of chromium oxides in conventional FeCr process slag, where chromium exists in two oxidation stages as Cr^{2+} and Cr^{3+}, is in the range 5-10 wt%. Due to quite high melting temperature of FeCr slags, only little experimental data are available on the viscosity of slags containing chromium oxides [2].

Forsbacka and Holappa *et al.*[3-5] have recently measured the viscosities of slags containing chromium oxides in several silicate systems. The experimental results support have provided useful data, improving the understanding the effects of chromium oxides on viscosity since the viscosity measurements have been carried out over wide composition ranges, as shown for example in Figure 1 for the SiO_2-CaO-CrO-$CrO_{1.5}$ system. The concentrations of divalent and trivalent chromium oxides in these slags have been determined through wet-chemical analysis. The systems studied SiO_2-CrO-$CrO_{1.5}$, SiO_2-Al_2O_3-CrO-$CrO_{1.5}$, SiO_2-MgO-CrO-$CrO_{1.5}$, SiO_2-CaO-CrO-$CrO_{1.5}$, SiO_2-Al_2O_3-MgO-CrO-$CrO_{1.5}$ and SiO_2-MgO-CaO-CrO-$CrO_{1.5}$ include all the main components, i.e. SiO_2, Al_2O_3, MgO, CaO, CrO and $CrO_{1.5}$, which constitute a typical FeCr process slag.

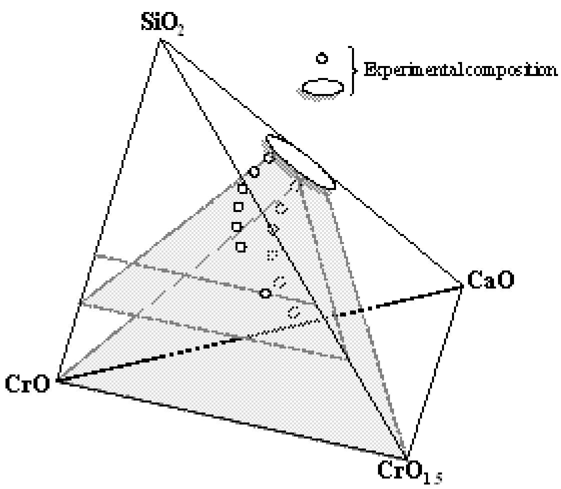

Figure 1: Slag compositions (mol%) in viscosity measurements by Forsbacka and Holappa in SiO_2-CaO-CrO-Cr_2O_3 system [4]

Tanaka *et al.* [6] have proposed a new method for estimation of viscosity of mold fluxes by applying the neural network computation. They concluded that the calculated results of the dependence of viscosity on the temperature and composition agreed better with the experimental results than some well-established physical models for viscosity.

In the present work, the neural network computation was applied to the viscosity of slags containing CrO and $CrO_{1.5}$ in order to predict the viscosities in ferrochromium process slags.

2. NEURAL NETWORK COMPUTATION

Neural network is a processing model based on the features known from the physiology of the human brain [7,8]. There are about 10 billion of brain cells (neurons) in a human brain. When the sum of the intensity of input signals to a neuron from some other neurons exceeds a certain critical value, new signals transmit to the next neurons as output signals. Figure 2 illustrates that the principle of neurons is translated into the computational organization (neuron model). In this model, the situation of the transmission of signals is represented by a sigmoidal function of the form shown in Equation 1.

$$f\left(\sum w_i \cdot s_i - h\right) = 1/\left\{1 + \exp\left(-\left(\sum w_i \cdot s_i - h\right)/T\right)\right\} \tag{1}$$

where: s_i is the input value, w_j is the connection weight, h is a critical value and T is a parameter. The output value y varies from 0 to 1.

Figure 3 is the schematic diagram of the back propagation approach in a layer-type neural network, which consists of three layers; the units in middle layer are connected with the units in the input and the output layers. After input values have been applied to the units in input layer, those are propagated to the output layer through the middle layer. The output values are compared to the teaching values, and the errors are computed for each output unit. Then, these error signals are transmitted backward from the output layer to each node between the layers in order to correct the weights there. These procedures are called "learning". "Learning" is repeated until the "learning" number reaches the target value or the error is reduced to an acceptable value. In the present study, the teaching value is a measured viscosity, and the input values are composed of the measurement temperature and the concentrations of oxide components. The "learning" was conducted with the software "Neurosim/L" produced by Fujitsu Ltd.[7] under the following conditions: the numbers of the units in middle layer were 5 for SiO_2-CaO-CrO-$CrO_{1.5}$ system and 7 for FeCr process slag, and the "learning" number was 1 000 000 in both systems. Then, the viscosities in several systems were calculated using this network.

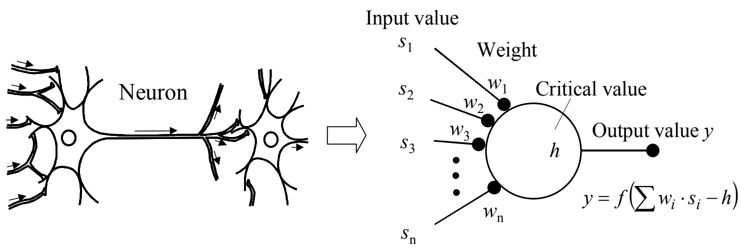

Figure 2: A concept of neuron model

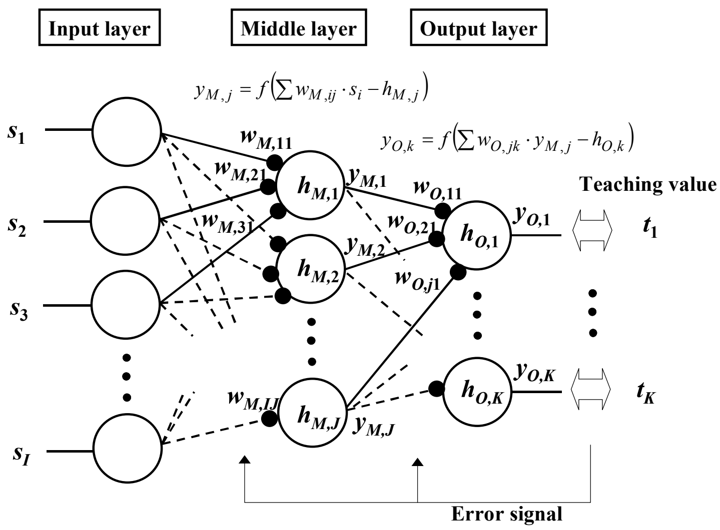

Figure 3: Schematic diagram of back propagation approach in a layer-type neural network

3. CALCULATION RESULTS

3.1 Viscosity In SiO_2-CaO-CrO-$CrO_{1.5}$ System

At first, the effects of di- and trivalent chromium oxides, CrO and $CrO_{1.5}$, on viscosity were examined in the basic system containing chromium oxides. The literature data[3-5,9-18] used here are listed in Table 1 (a). The total number of literature data is 306. Figure 4 shows the comparison between the experimental viscosity and the calculated viscosity with neural network computation. The calculation results are in good agreement with the experimental data in this system. The average error in these systems assessed using Equation 2 is 14.6 %.

$$\text{Average error} = 1/N \cdot \sum_{1}^{N} \left| \eta_{Calc} - \eta_{Expe} \right| / \eta_{Expe} \times 100 \quad (\%) \tag{2}$$

where: the η_{Expe} and η_{Calc} values correspond to the experimental viscosity values in the literature and the calculated viscosity, respectively. *N* corresponds to the number of the literature data.

Table 1: Literature data used for the estimation of viscosity in SiO_2-CaO-CrO-$CrO_{1.5}$ slags (a) and in FeCr process slags (a)+(b)

	System	Ref.
(a)	SiO_2	[9-14]
	SiO_2-CaO	[3,5,15-18,20]
	SiO_2-CrO-$CrO_{1.5}$	[5]
	SiO_2-CaO-CrO-$CrO_{1.5}$	[3,4]
(b)	Al_2O_3	[16,19]
	SiO_2-Al_2O_3	[16,20]
	SiO_2-MgO	[5,20-22]
	SiO_2-Al_2O_3-CaO	[16]
	SiO_2-MgO-CaO	[5,20,22-24]
	SiO_2-Al_2O_3-MgO-CaO	[23-27]
	SiO_2-Al_2O_3-CrO-$CrO_{1.5}$	[5]
	SiO_2-MgO-CrO-$CrO_{1.5}$	[5]
	SiO_2-Al_2O_3-MgO-CrO-$CrO_{1.5}$	[5]
	SiO_2-MgO-CaO-CrO-$CrO_{1.5}$	[5]

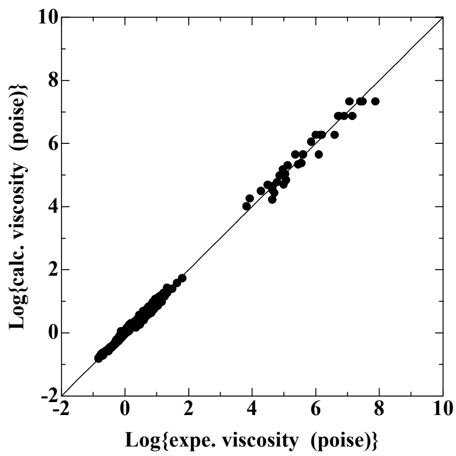

Figure 4: Comparison between experimental and calculated viscosities using neural network computation in SiO_2-CaO-CrO-$CrO_{1.5}$ slags

Figure 5 shows viscosities in (48.3SiO_2-51.7CaO)-CrO-$CrO_{1.5}$ (mol%) system at 1973 K. The calculated iso-viscosity curves reasonably satisfy the composition dependence of the measured values[4] in this quaternary system. These results confirm that the viscosities of slags in SiO_2-CaO-CrO-$CrO_{1.5}$ system can be evaluated by the neural network computation.

The calculation results with neural network computation at constant content of 40mol% SiO_2 in SiO_2-CaO-CrO-$CrO_{1.5}$ at 1923 K are shown in Figure 6. The replacement of CaO by CrO results in a decrease of viscosity, whereas replacement by $CrO_{1.5}$ slightly increases the viscosity. This result means that in this system CrO works stronger than CaO as a basic oxide, which decreases viscosity. On the other hand, $CrO_{1.5}$ seems to be a little weaker basic oxide than CaO in this estimation. Generally, $CrO_{1.5}$ is assumed to be a weak basic oxide with amphoteric characteristics and CaO is known as a strong basic oxide [3,4].

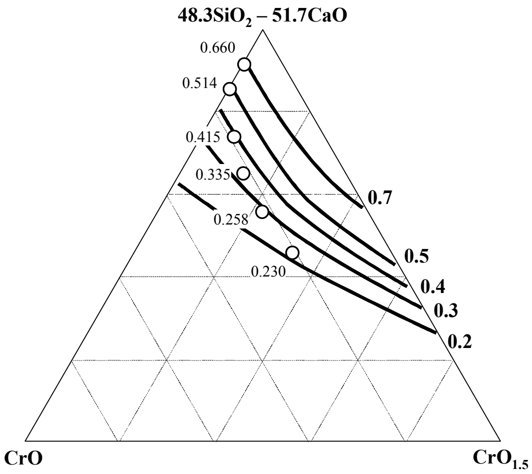

Figure 5: Viscosity (poise) in (48.3SiO$_2$-51.7CaO)-CrO-CrO$_{1.5}$ (mol%) system at 1973 K. Open circles are measured viscosities by Forsbacka and Holappa[4]. Solid lines are iso-viscosity lines calculated by neural network computation

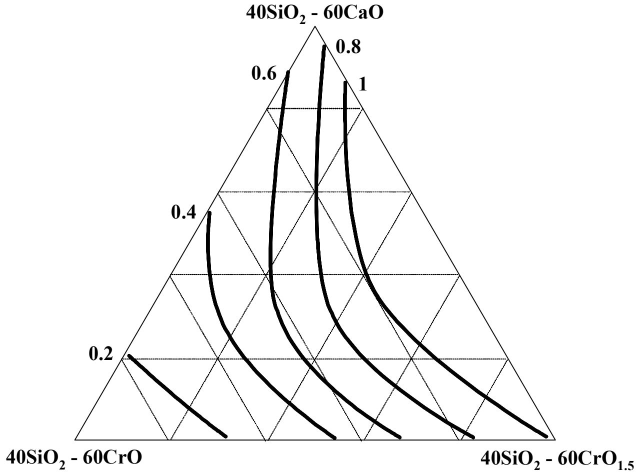

Figure 6: Effect of CaO, CrO and CrO1.5 on viscosity (poise) in 40SiO2-CaO-CrO-CrO1.5 (mol%) system at 1923 K. Solid lines are iso-viscosity lines from neural network computation

3.2 Viscosity In FeCr Process Slag

The calculation of the viscosities in FeCr process slags with neural network computation is based on the experimental data[3-5,13-27] of the systems listed in Table 1 (a) and (b). The number of data points in all systems is 1559. The comparison between the experimental viscosity and the calculated viscosity with neural network computation is shown in Figure 7. Neural network computation reproduces the experimental data well over the wide viscosity range in 10^{-1} - 10^{8} poises. The average error in Equation 2 was 21.6 %.

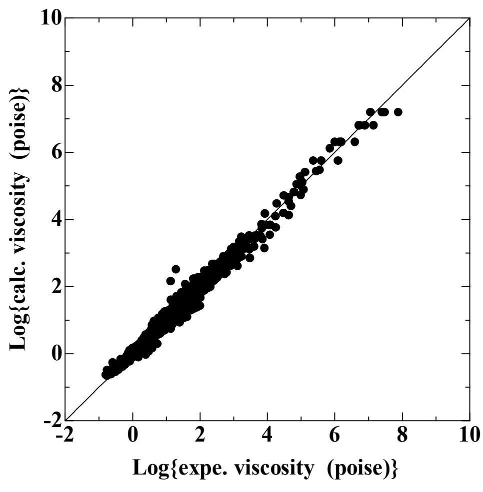

Figure 7: Comparison between experimental viscosity and calculated viscosities using neural network computation in SiO$_2$-Al$_2$O$_3$-MgO-CaO-CrO-CrO$_{1.5}$ slags

The results calculated by neural network computation are compared with the experimental data[5] in the two quinary systems containing CrO and CrO$_{1.5}$ in Figures 8 and 9. The former shows the temperature dependence of viscosity in SiO$_2$-Al$_2$O$_3$-MgO-CrO-CrO$_{1.5}$ system, and the latter shows the effect of the ratio CrO to CrO$_{1.5}$ on the viscosity in SiO$_2$-MgO-CaO-CrO-CrO$_{1.5}$ system at 1923 K. The calculation results are in agreement with the experimental data with three compositions in the temperature range above 1800 K in Figure 8. The measurements indicate that the viscosity decreases with increasing the total content of chromium oxides, while the calculations predict that a decrement of CrO/CrO$_{1.5}$ yields a slight lowering in viscosity in Figure 9. The calculation result of neural network computation satisfies those composition dependencies. These results mean that the neural network computation is applicable to the estimation of viscosities in the multi-component system composed of the main constituents in ferrochromium process slag.

Figure 10 shows the calculation results of the effect of chromium oxides CrO and CrO$_{1.5}$ on the viscosities of FeCr process slags at 1923 K. The main components (SAMC) in

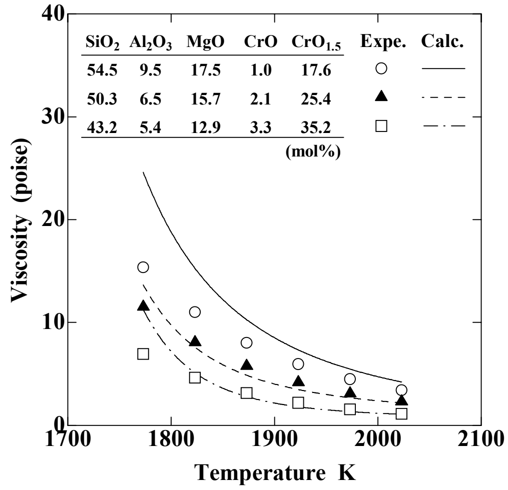

Figure 8: Temperature dependence of viscosity in SiO_2-Al_2O_3-MgO-CrO-$CrO_{1.5}$ system. Symbols show viscosities measured by Forsbacka and Holappa et al.[5]

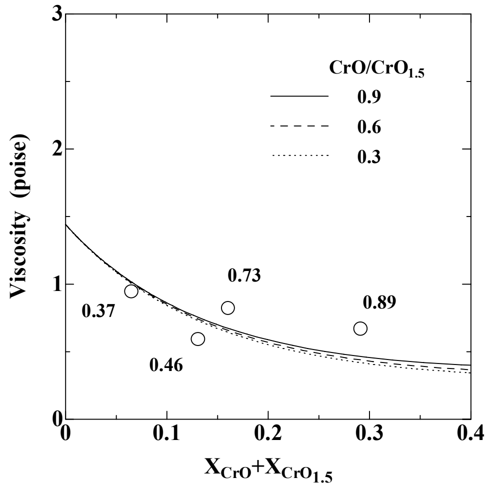

Figure 9: Effects of CrO and $CrO_{1.5}$ on viscosity (poise) in {45.6SiO_2-30.3MgO-24.4CaO(mol%)}-CrO-$CrO_{1.5}$ system at 1923 K. Open circles are viscosities measured by Forsbacka and Holappa et al.[5]. The numbers near the circles show the ratio CrO/$CrO_{1.5}$, respectively. Solid, dashed and dotted lines are the calculation results with neural network computation

the slag were chosen to correspond with the composition 35SiO_2-30Al_2O_3-28MgO-7CaO in wt%, which is equal to 34.3SiO_2-17.3Al_2O_3-41.0MgO-7.4CaO in mol%. Further the final slag contained from 0 to 10 mol% of CrO + $CrO_{1.5}$. In this estimation, the viscosities of FeCr process slags are in the range 1-2 poises in the concentration range of chromium oxides of 0-10 mol%. Increasing concentration of chromium oxides leads to a decrease in viscosity, the divalent CrO having a stronger effect on the viscosity than the trivalent $CrO_{1.5}$.

4. CONCLUSIONS

Neural network computation has been applied to estimate the effect of chromium oxides on the viscosities of slags as well as to predict the viscosities in typical FeCr process slags. It was found that the neural network computation reproduced the composition dependence of the viscosity of molten slags containing chromium oxides in multi-component systems. In this estimation, both chromium oxides decrease the viscosity of FeCr process slags, whilst CrO has a slightly stronger influence on viscosity than $CrO_{1.5}$.

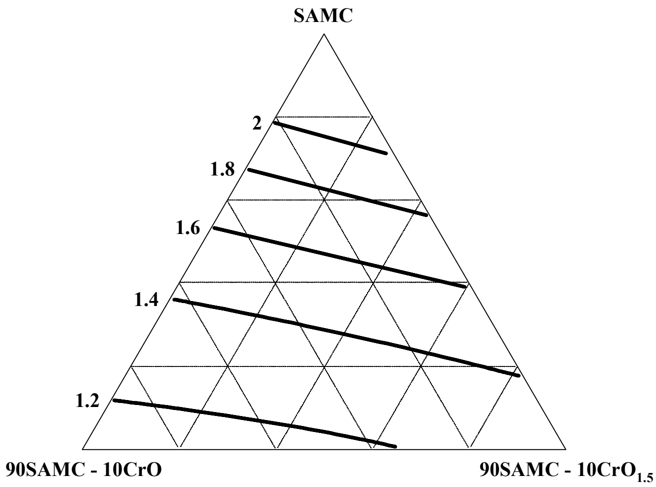

Figure 10: Iso-viscosity lines (poise) in FeCr process slag at 1923 K. SAMC is 34.3SiO_2-17.3Al_2O_3-41.0MgO-7.4CaO (mol%)

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