

## **THERMO-CHEMICAL MODELLING OF THE PRODUCTION OF FERRO-CHROMIUM IN SUBMERGED-ARC FURNACE**

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Several studies have been reported in literature on the thermochemistry of production of ferro-chromium. Experimental studies have been carried out to understand the kinetics of reduction of oxides and to study the equilibrium between slag and metal in the furnace. However, a quantitative model of the thermochemistry of the process in any region of the furnace is yet to be reported. Pre-reduction of the ore has been recommended and also employed as a means of reducing the power consumption in the furnace. However, the effect of this on the temperature profile in the furnace is yet to be explored. This communication reports a thermochemical model for the production of ferro-chromium in submerged-arc furnace and a model to map the temperature profile in the furnace. The effect of pre-reduction on the temperature profile has also been assessed.

### **INTRODUCTION**

Thermochemistry of the production of ferro-chromium in the submerged-arc furnace, including the kinetics of reduction and the thermochemical equilibrium among the various phases have been studied by several investigators [1-12]. In the upper regions of the furnace, temperatures are low. Reaction kinetics play a major role in this region. The charge melts around 1500°C. The oxides of chromium and iron are reduced before this temperature is reached and the charge descends into the slag layer [8,9]. It can be expected that the chemistry of the metal and slag will be controlled by the thermochemical equilibrium between these two phases above this temperature. The high temperatures will also promote attainment of thermochemical equilibrium in local regions, if not over the whole zone. It is this equilibrium that will control the ultimate chemistry of the metal tapped.

### **THERMOCHEMICAL ANALYSIS**

In the present study the thermochemistry of the process was analysed in the zone where liquid metal and slag interact to produce final metal and slag. It was assumed that equilibrium prevail between the slag and the metal. Vertical descent and ascent of the condensed phases and gas respectively were assumed. The equilibrium state of the system involving the three phases was predicted at each temperature. A free energy-minimization programme was utilized for this purpose.

It was found that silicon was present in the hot metal at temperatures above 2000°C. Below this temperature silicon was not present in the hot metal in equilibrium with the slag. Therefore, from the point of view of partitioning of silicon between the metal and

slag it was possible to divide the high temperature regions of the furnace into two zones: (a) those regions where the temperature was 2000°C or above and (b) those regions where the temperature was below this. These zones have been schematically indicated as 'B' and 'C' in Fig.1. Since the identification of these two zones was arrived at by assuming local thermodynamic equilibrium in each zone, it was also possible to recognise the presence of another zone where thermodynamic equilibrium does not prevail. This was designated as zone 'A' in Fig.1. The boundary between the zones 'A' and 'C' has to be identified through experimental investigations. The chemistry of the metal does not change significantly with temperature in the zone 'C'. In zone 'B', the composition of the metal changed to some extent with temperature.

### PREDICTION OF SILICON LEVEL IN THE HOT METAL

The hot metal tapped is a mixture of the metal passing through the zones 'B' and 'C'. The ratio of the mass of the metal passing through the zone 'B' and through the volume of the furnace lying between the same horizontal levels, depends on the relative sizes of these two regions and the descent rate of the material through these. This ratio is denoted as 'x'. This gives the relative size of the B-zone.

Data were collected from a plant producing ferro-chromium over a period of two months. The magnitude of 'x' was predicted for the different taps. The level of silicon in the hot metal correlated with the ratio 'x' as given below:

$$\text{wt\% Si} = 0.24 + 12.0 x$$

Data collected from the same plant after an interval of six months produced the following correlation

$$\text{wt\% Si} = 0.43 + 14.0 x$$

Data collected from another plant responded as follows:

$$\text{wt\% Si} = 0.32 + 15.0 x$$

The striking similarity between the various expressions emphasises the role of the B-zone in controlling the level of silicon in the hot metal. It may be noticed that the expressions predict that if the B-zone does not exist, the level of silicon in the hot metal will be low, further emphasising the role of this zone. The chemistry of the hot metal was predicted using this model. Therefore is good agreement between the predicted and observed composition (Table.I).

Table I Predicted and observed metal chemistry

Cr		Fe		C	
Pred.	Obs.	Pred.	Obs.	Pred.	Obs.
64.3	63.8	22.9	25.5	9.9	7.7
65.0	62.0	22.0	26.2	9.7	8.0
61.2	62.1	25.2	27.3	10.9	7.9
63.7	62.7	23.3	26.9	10.4	7.9
64.6	63.5	21.4	26.0	11.3	7.9

### MODELLING OF THE THERMAL PROCESS IN THE S.A.F.

Simulation of the thermal process in the S.A.F. involves complex interaction of a moving bed of solids, heat generation due to chemical reaction, counter current movement of the gases and the generation of heat in the electrode, slag and metal due to the flow of

electricity. In this study, a computer programme was developed based on a transient, rather than steady-state analysis of the furnace, often cited in literature. Although simulation is computationally more time-consuming, it gives realistic information of furnace operation during start-up or shut-down of the furnace.

Due to its complexity, the three electrode, three dimensional furnace was modelled as a single electrode, two dimensional one. The distribution of current in electrode, in both radial and axial and in the slag-metal system was estimated based on proportions obtained from literature [14]. An equivalent electrode diameter was assumed which would have the same total cross-sectional area of the three electrodes of the furnace. These concepts were then applied to an industrial S.A.F. operating at 55 kilo amperes (3-phase). The thermal conductivity of packed bed can be estimated through several methods, as cited in literature [15-17]. These involve effects of thermal conductivities of the solid and gaseous phases, mass flow rate of gas and the radiation heat transfer between particles of the bed. Expressions have been obtained for both radial and axial effective thermal conductivities for moving beds. One of the major assumptions in all the models is that there is negligible dust in the gas to affect the radiative and convective contributions in the voids between the particles. At low temperatures, the effective thermal conductivity can be significantly affected by the void fraction of the bed, particularly if the gas velocities are low. In this analysis, thermo-physical properties of the ore, coke and gas were taken as functions of temperature with data obtained from literature [18]. Operating parameters of the furnace and dimensions are given in Table II.

Table.II Operating parameters

Charges	Tonnes/day	Properties of the charge	
Hard lump ore	125.58	$K_{ore}$	2.0 W/m.K
Friable ore	23.40	$K_{coke}$	40.0 W/m.K
Sinter pellets	185.63	$K_{slag}$	57.0 W/m.K
Coke	78.67	$K_{el}$	40.0 W/m.K
		Bed porosity	30%
		Density of ore	5000 Kg/m <sup>3</sup>
		Density of slag	2000 Kg/m <sup>3</sup>
		Density of electrode	1900 Kg/m <sup>3</sup>

The expressions for mass and energy transport for the gaseous and solid phases can be written as:

$$C_{p_i} G_i \delta T / \delta z = (\delta / \delta z) (K_i \delta T / \delta z) + 1/r \delta / \delta r (r k_i \delta T / \delta z) + S_i \quad (1)$$

$$C_p G_g \delta T / \delta z = ah (T_g - T_{ch}) \quad (2)$$

with boundary conditions:

$$\begin{aligned} \delta T / \delta r &= 0 \text{ at the centre of the electrode} \\ K_i \delta T / \delta r &= q_i \text{ at furnace wall} \\ K_b \delta T / \delta z &= q_2 \text{ at furnace bottom} \\ K_{el} (\delta T / \delta r)_{el} &= k_{ch} (\delta T / \delta r)_{ch} \text{ at the charge-electrode interface} \end{aligned}$$

Here, 'i' stands for solid phases and 'g' for the gas phase.  $K$ ,  $C_p$ ,  $G$  are the thermal conductivity, specific heat and mass flow rates, respectively.  $S$  is the source term for heat generation per unit volume.

At the surface of the charge,

$$k_{ch} (\delta T / \delta z)_{ch} = h_s (T - T_A) \quad (3)$$

where  $h_s$  is the surface heat transfer coefficient,  $T$  is the surface temperature and  $T_A$  is the ambient temperature and

$$a = 6(1-\epsilon) / d_p \quad (4)$$

Where ' $\epsilon$ ' is the void fraction of the bed and  $d_p$  the mean diameter of the particles.

The gas-solid heat transfer coefficient of the bed was determined from empirical considerations for Nusselt number given in [19], for various Reynolds numbers denoted by:

$$Re = Gg d_p / \mu \quad (5)$$

where  $\mu$  is the viscosity of the gas.

Ohmic (resistance) heating in the electrode and slag-metal was computed using the formulation:

$$Q = 1/\sigma |\vec{j}|^2 \quad (6)$$

$$\text{where } |\vec{j}|^2 = \sqrt{J_z^2 + J_r^2} \quad (7)$$

$J_z$  and  $J_r$  are the axial and radial components of current density and  $\sigma$  is the electrical conductivity of the medium.

For porous aggregates with two kinds of solid particles

$$K_{eq} = (k_0 f_0 + k_1 f_1 A_1 + k_2 f_2 A_2) / (f_0 + f_1 A_1 + f_2 A_2) \quad (8)$$

$$A_1 = 3k_0 / (2k_0 + k_1) \quad (9)$$

$$A_2 = 3k_0 / (2k_0 + k_2) \quad (10)$$

Here the  $k$ 's represent thermal conductivities and  $f$ 's, the volume fractions ('0', for gas and '1' and '2' for solid phases).

The charge comprising of ore, coke and flux was assumed to be in a state of plug flow in the direction of gravity with gas (assumed to be mainly carbon monoxide) to move in the counter current direction.

The energy conservation equations were solved numerically using a finite difference scheme with appropriate boundary conditions. The resistance heating was assumed to be mainly in the electrode and slag-metal system, since the current densities in the charge are

usually negligible. Simulations were conducted for various levels of pre-reduction of ores, namely, 0,20,40,60 and 80%. The model can handle either a specific arc temperature between electrode and slag or energy input to evaluate the arc temperature. Wall surface heat transfer coefficients were taken from literature [14], while the heat flux at the bottom of the furnace was estimated from actual temperature measurements at the bottom of the industrial furnace and the dimensions and compositions of the refractories.

### DISCUSSION

From the modelling of the temperature profile in the furnace, the magnitude of the ratio 'x' was predicted. At 0% pre-reduction, the relative size of the B-zone thus obtained is 0.26. This is consistent with the predictions made on the basis of the thermochemical model (Table III). Thus, the size of the B-zone estimated from two different models are consistent with each other. This strengthens the confidence in the thermochemical model of the process proposed in this communication.

Table.III Size of the B-zone computed for different tappings

Tap No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Size	23	29	29	19	29	18	25	33	30	23	25	31	34	33

Analysis of data from industrial plants indicates that the relative size of the B-zone varies from 16% to 35%. Fluctuations in power supply cause the B-zone around each electrode to expand or shrink during a tapping cycle. Hence control of power supply is required to control the size of this zone.

Efforts are being made the world over to reduce the power consumption in the S.A.F. One of the strategies adopted to achieve this is to charge pre-reduced ore into the furnace. Depending on the degree of pre-reduction, the heat required for the chemical reactions inside the furnace will decrease. This will also alter the volume of the gas generated. Both these factors can alter the temperature profile inside the furnace. The effect of pre-reduction on the temperature profile was studied. The oxides reduced, the extent of reduction and the product formed depend on the temperature and the time available for reduction. Several studies have been carried out in the laboratory to study the sequence and extent of reduction at different temperatures [2-4]. It was assumed that these data collected in the laboratory would represent the reactions in the S.A.F. also. These data were used to construct the temperature profile at different degrees of pre-reduction.

Up to 40% pre-reduction, there is no significant change in the temperature profile. The change in the profile was significant at 40% pre-reduction compared to that at 0% pre-reduction (Figs.2-3). The profiles obtained for pre-reduction levels of 40-80% were similar. Hence higher levels of pre-reduction influence the temperature profile and this must be taken into consideration when controlling the level of silicon which depends on the temperature profile in the furnace.

### SUMMARY

A thermochemical model for the production of ferro-chromium in the submerged-arc furnace has been reported. The predictions of the model are consistent with observations. The temperature profile in the furnace has been mapped. This profile corroborates with the predictions based on the thermo-chemical model. The effect of pre-reduction on the temperature profile in this furnace has been analysed and reported.

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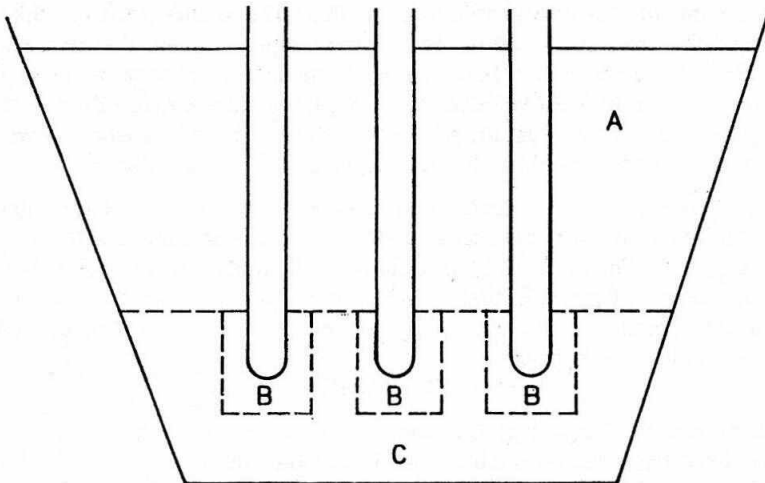


Fig.1. The thermochemical zones in the S.A.F

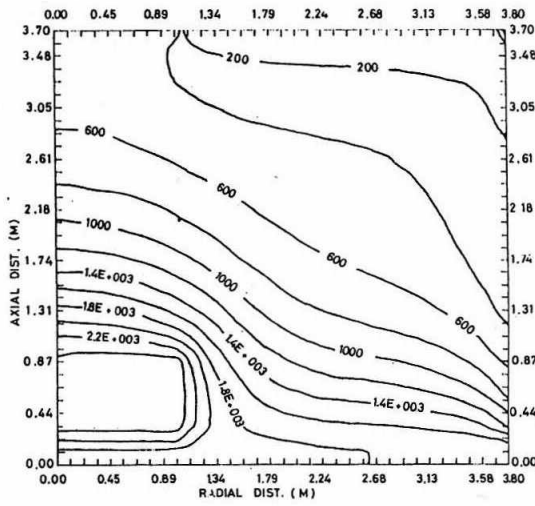


Fig. 2. Temperature profile in the S.A.F. at 0% pre-reduction of charge

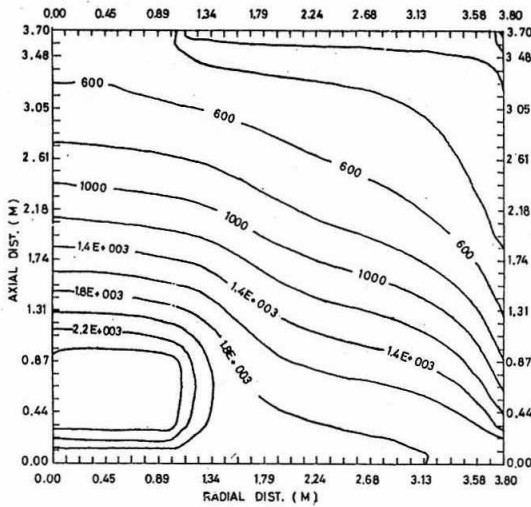


Fig.3. Temperature profile in the S.A.F. at 40% pre-reduction of charge