

Mathematical modelling and the influence of process parameters on the temperature profile in a submerged arc furnace producing ferro-chromium

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ABSTRACT

Control of the temperature profile is a crucial factor for optimising the energy consumption and regulating the quality of the hot metal produced in submerged arc furnace. Factors such as the heat generated at the electrodes, the heat loss, the heat consumed by chemical reactions, the packing density of the charge materials etc. determine the profile. This in turn decides the production rate and the chemistry of the hot metal. Controlling the level of impurities in the hot metal such as the level of silicon in ferro-chromium can be achieved through the mapping of the temperature profile and regulating the process accordingly. The communication describes the mathematical modelling of the temperature profile in the submerged arc furnace and analyses the influence of several process parameters on the same.

INTRODUCTION

The production rate and the quality of ferro-chromium in a submerged arc furnace (SAF) are largely controlled by the temperature profile prevailing in the furnace. These influence the specific power consumption in the furnace, in turn. An understanding of the influence of the process parameters on the temperature profile in the furnace is vital for regulating the process to obtain consistent product quality and to optimize energy consumption. The temperature profile is determined by the heat generated at the electrodes; the thermal and electrical conductivities of the slag and the charge materials; the void fraction; the heat generated or consumed in chemical reactions; by the heat loss from the furnace; by the pre-heat in the charge etc. A mathematical model of the temperature profile in the SAF has been developed and applied

to the production of ferro-chromium. A thermochemical analysis of the process⁽¹⁾ predicted that the silicon level in the hot metal tapped was a function of the temperature profile in the furnace. From this analysis, it was possible to predict the presence of three thermochemical zones and the relative sizes of the major zones. The mathematical model of the temperature profile is useful in precisely delineating the location and the geometrical shapes of these zones and in providing more reliable predictions on the quality of the hot metal. It will also help in analysing the effect of various process parameters on the temperature profile and in regulating the same.

THERMOCHEMICAL MODEL

A general thermochemical model is being developed at the National Metallurgical Laboratory to analyse the production of ferro-alloys in the SAF. This model considers the furnace to consist of a number of temperature zones (Fig. 1). The chemistry of the charge material is treated as it descends the furnace traversing the various temperature zones. The nature and the extent of the chemical reactions in each zone is determined by the temperature of the zone and the time taken by the material to traverse the same. The temperature profile is, in turn, affected by the extent of chemical reactions and the descent rate of the charge through the different zones. From the thermochemical model, the presence of three major thermochemical zones (as distinct from the

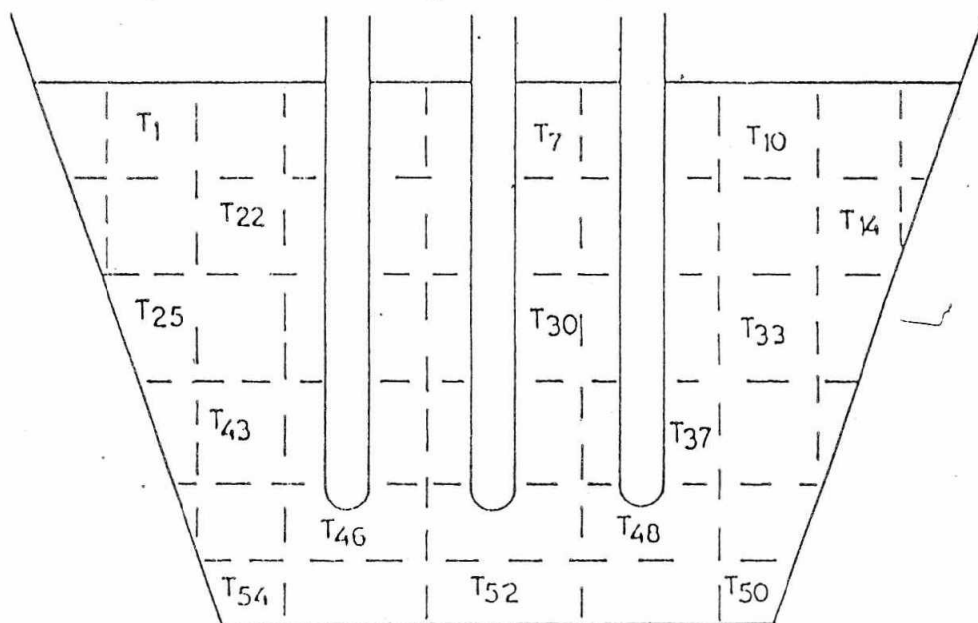


Fig. 1 : Schematic representation of the temperature zones inside the furnace

temperature zones), was recognized. These zones are depicted in Figure 2. The shape and the relative sizes of these zones have to be ascertained by mapping the temperature profile of the furnace. Figure 2 is only a schematic representation of these. From the thermochemical model, the chemistry of the hot metal was predicted. The predictions are in good agreement with the reported chemistry of the metal from the plant (Fig. 3). A precise delineation of the thermochemical zones and tracing of the chemistry of the material in well-defined temperature zones will make the predictions of the thermochemical model to be more consistent with the observed data. A general model which combines the mathematical model of the temperature profile and the thermochemical model of the process will provide a powerful tool to precisely regulate the process to achieve consistent metal quality at optimum energy consumption.

MODELLING OF THERMAL PROCESS

Simulation of thermal profiles in the SAF involves the complex interaction of mobile solids, gases and heat generation due to chemical as well as the electrical processes occurring inside the furnace. The counter-current packed bed system comprises of the cold solid charge moving in the direction of

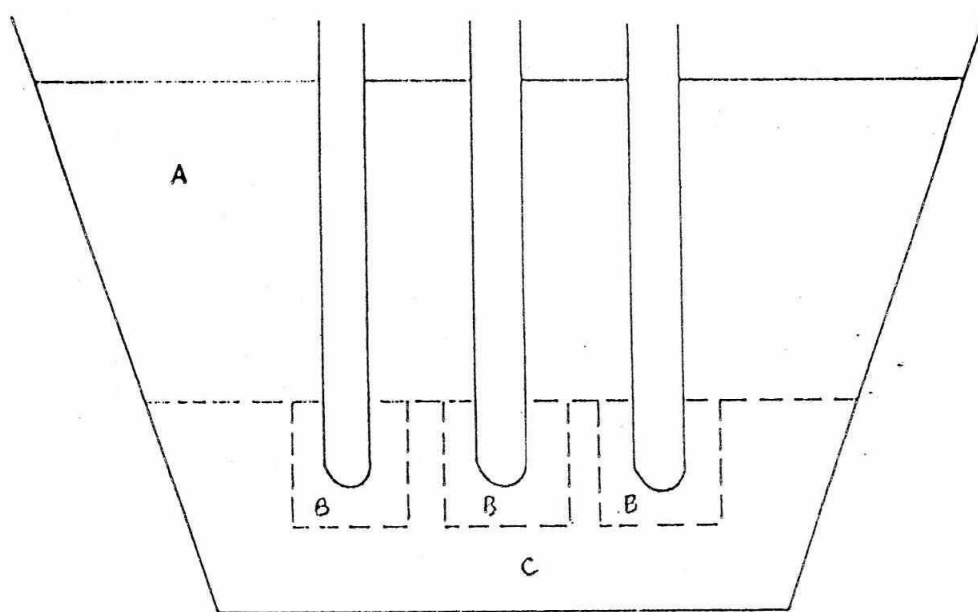


Fig. 2 : Schematic representation of the three major thermochemical zones

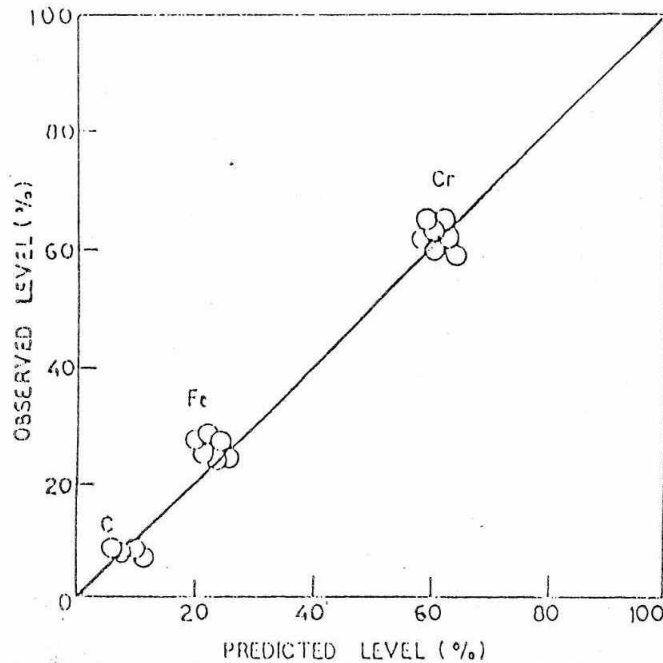


Fig. 3 : Comparison of model prediction with observation

gravity and hot gases moving in the opposite direction. The distribution of current in the furnace depends on various factors, such as the electrical conductivities of the electrodes, charge, slag and metal, their respective geometries, and the type of electrical connection, i.e., whether star or delta.

Several workers^[2-5] have made attempts to evaluate the current density distribution in the various phases by employing principles of A.C. electromagnetics, with appropriate boundary conditions. A system of energy conservation equations for countercurrent packed beds were also solved simultaneously. Published literature however, has restricted itself to only a 2-D single electrode approximation of the 3-phase, 3-electrode SAF. This approximation is obvious due to the complexities in modelling a three electrode system in three dimensions.

In this study, an existing industrial ferro-chrome furnace was simulated. The dimensions and operating parameters are depicted in Table 1. The slag and metal were assumed to be a single phase for simplicity. The equations employed for energy conservation were modified from those used in ref. [5] after accounting for transient phenomenon instead of steady state. Gas generation rates and heat generation per unit volume were computed in the thermochemical model and the values inserted in the equations which compute temperature profiles.

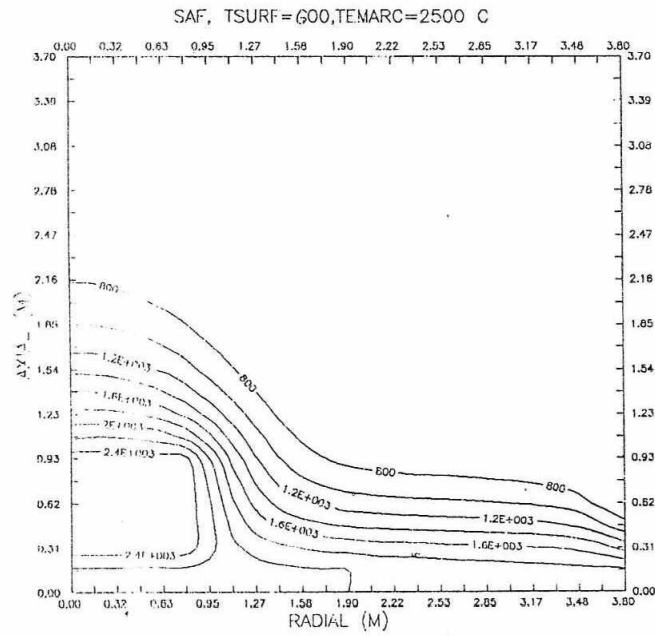


Fig. 4: Temperature profile for charge entering at 600°C and electrode tip at 2500°C

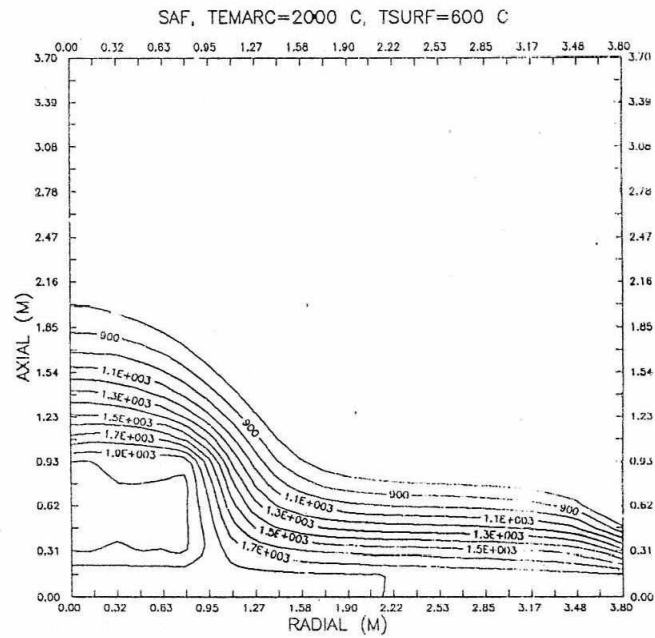


Fig. 5: Temperature profile for charge entering at 600°C and electrode tip at 2000°C

$$C_{pi} G_i \frac{\delta T}{\delta z} = \frac{\delta}{\delta z} (K_i \frac{\delta T}{\delta z}) + \frac{1}{r} \frac{\delta}{\delta r} (r K_i \frac{\delta T}{\delta r}) + S_i \quad \dots 1$$

$$C_{pg} G_g \frac{\delta T}{\delta z} = ah (T_g - T_{ch}) \quad \dots 2$$

The boundary conditions were as follows :

$$\frac{\delta T}{\delta r} = 0 \quad \text{at centre of electrode} \quad \dots 3$$

$$k_i \frac{\delta T}{\delta r} = q_i \quad \text{at furnace wall} \quad \dots 4$$

$$k_{sl} \frac{\delta T}{\delta z} = q_2 \quad \text{at furnace bottom} \quad \dots 5$$

$$K_{el} (\frac{\delta T}{\delta r})_{el} = K_{ch} (\frac{\delta T}{\delta r})_{ch} \quad \text{at charge-electrode interface} \quad \dots 6$$

At the charge-slag interface :

$$C_{pi} G_i T + k_i \frac{\delta T}{\delta z} = \text{constant} \quad \dots 7$$

$$\text{and } T_g = T \quad \dots 8$$

The index 'i' represents charge, electrode, or slag phases. 'C_p' is the specific heat, 'T' the temperature, 'h' the surface heat transfer coefficient, 'a' the particle surface area, 'G' the mass flow rate, 'S' the heat generation rate per unit volume. 'q₁' and 'q₂' are the estimated heat fluxes at the furnace wall and bottom respectively. The subscripts ch, el, sl and g correspond to the phases — charge, electrode, slag and gas respectively.

At the charge surface,

$$T_{surf} = T_0$$

where T₀ is the measured temperature above the charge inside the furnace and varies from 400 to 750°C.

In this study, the arc temperature was assumed constant in the zone below the electrode, and varied in steps from 2000 to 3000°C. A transient heat transfer analysis was then conducted with present values of heat and gas

generation rates as a function of temperature, based on the thermochemical model. An equivalent electrode diameter was assumed by summation of the three electrodes of an industrial furnace.

Ohmic heating was computed using :

$$H = \frac{1}{\sigma} \vec{J}^2 \quad \dots 10$$

where 'σ' is the electrical conductivity of the phase and 'J' is the resultant current density.

The specific surface area of the packed bed can be computed using :

$$\vec{J} = (\sqrt{J_z^2 + J_r^2}) \quad \dots 11$$

$$a = 6(1 - \epsilon)/d_p \quad \dots 12$$

where 'ε' is the bed void fraction and d_p the mean particle diameter.

For porous aggregates comprising of two types of solids in a continuous fluid phase, the equivalent thermal conductivity can be computed by :

$$k_{eq} = \frac{(k_0 f_0 + k_1 f_1 A_1 + k_2 f_2 A_2)}{(f_0 + f_1 A_1 + f_2 A_2)} \quad \dots 13$$

The subscript is for fluid phase and 1 and 2 for solid phases, 'f' is the volume fraction of the constituent and

$$A_1 = 3k_0 / (2k_0 + k_1)$$

$$A_2 = 3k_0 / (2k_0 + k_2)$$

In this investigation, ore constituted one of the solid phases and coke the other solid phase and gas was assumed to be mainly carbon monoxide. The heat transfer coefficient was estimated for a range of Reynold's numbers based on empirical Nusselt number correlations given in ref.^[5].

$$R_e = G_g d_p / \mu \quad \dots 14$$

where 'μ' is the viscosity of the gas at the temperature under consideration.

RESULT AND DISCUSSION

Figures 4-6 provide the temperature profiles prevailing in the furnace derived from the model. The temperature profile depends on the temperature of the electrode, the heat losses from the furnace, the current density in the (slag + metal) layer and on the pre-heat in the charge. The heat losses from the walls and the bottom of the furnace do not vary significantly, over a short period.

However, the power supply to the electrodes significantly alters the temperature at the electrodes. The effect is also felt quickly. Similarly the electrical properties of the charge material (such as specific electrical resistance etc.) can be altered by a change in the chemistry of the material supplied. It is not clear as to what extent these properties change in the present system considered. Apart from these, the packing density of the charge in the furnace also can affect the temperature profile, by altering the heat loss from the top of the furnace through the gas. This factor was assumed to remain constant.

The effect of the temperature at the tip of the electrode on the temperature profile was explored. Figures 4 and 5 compare the isotherms at electrode tip temperatures of 2500°C and 2000°C, respectively. In these cases, the charge has been assumed to be fed into the furnace at 600°C. A significant difference between two profiles is the total area covered by the isotherms at 2000°C or above. Figures 4 and 6 compare the effect of current densities through the slag layer, on the temperature profile. A 50% reduction in current density (in Fig. 6) significantly alters the temperature profile.

From a thermochemical model of the production of ferrochromium in S.A.F.(1), it was predicted that the level of Silicon in the hot metal was controlled by the ratio of the material passing through the thermochemical zone (zone B of figure 2) where the temperatures are at 2000°C or above to the total material passing through the zones where the temperatures are at 1600°C or above. This ratio depends on the relative sizes of these zones and the relative descent rate of the material through these. Assuming that the latter is constant, this ratio was deduced from the isothermal profiles obtained. The total area under the isotherms of 2000°C and above and the same above 1600°C were calculated. The ratio thus obtained is reported in Table 2.

When the temperature of the electrode is 2000°C, the relative size of the B-zone (the ratio discussed above) of Fig. 5, reported in Table 2 is 0.15. This figure is 0.35 in the case of the second profile (Fig. 4) where the electrode temperature is 2500°C. From an analysis of data from two different industrial plants, it was concluded earlier^[1] that level of silicon in the hot metal was related to the size of the B-zone through :

$$\%Si = -0.4 + 14.2X$$

where %Si represents the wt% of Silicon in the hot metal and X is the relative size of the B-zone. It may be noted that the expression above indicates that the silicon level in the hot metal approaches zero when the B-zone disappears. Therefore, to control the silicon level in the hot metal, it is necessary to control the size of this zone. The present analysis brings out clearly that the electrode temperature significantly controls the size of this zone. The size of the B-zone predicted earlier from thermochemical analysis and that derived in the present

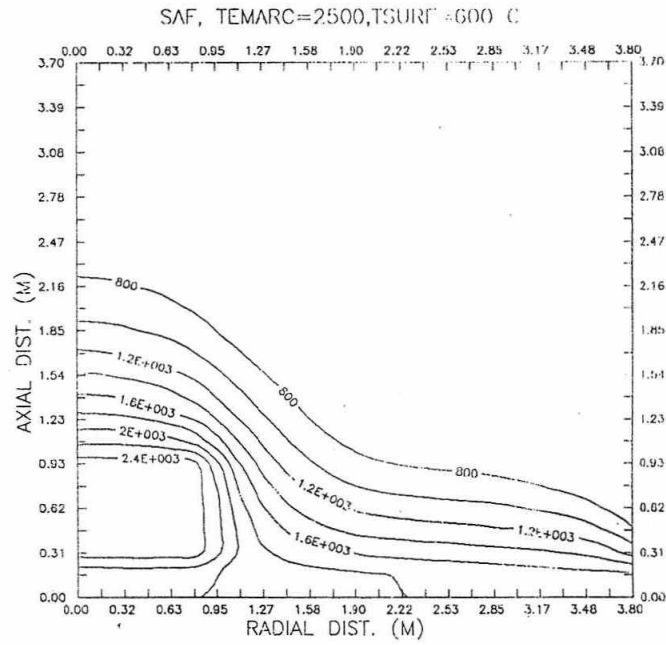


Fig. 6 : Temperature profile at higher current density

Table 1

| Dimension of the furnace | Total charge (Tonnes / day) |
|--------------------------|-----------------------------|
| Uppermost dia. : 8860 mm | Total hard lumps : 120.58 |
| Lowermost dia. : 7260 mm | Total friable ore : 23.397 |
| Height : 3190 mm | Sinter pellets : 185.63 |
| | Coke : 78.67 |
| | Quartz : 25.85 |
| | Power supplied : 486 MWH |

Table 2 : Influence of various parameters on the size of B-zone

| Case no. | Ts. (°C) | Te. (°C) | X |
|----------|----------|----------|------|
| 1 | 600 | 2500 | 0.35 |
| 2 | 600 | 2000 | 0.15 |
| 3 | 300 | 2500 | 0.37 |
| 4 | 300 | 2000 | 0.16 |
| 5 | 600 | 2500 | 0.40 |

Ts - Temperature of the material charged

Te - Temperature of the electrode tip.

X - Relative size of B-zone

analysis are in good agreement. The temperature of the charge entering the furnace was changed from 600°C to 300°C. The size of the B zone is not altered significantly as inferred from Table 2. In this table, the last entry reports the size of the B-zone on increasing the current density by 50% of the magnitude assumed for case 1. The size of the B-zone changes to a noticeable extent.

From the analysis, it is concluded that pre-heating of the charge has no effect on the size of the B-zone. Any change in the current density through the (slag+metal) layer alters this. A significant change occurs when the electrode temperature is changed by 500°C. Usually it is not possible to control the current densities at the (slag + metal) layer since the nature of the raw materials depends on their source over which little control can be exercised in practice. To enable smooth operation of the furnace and ensure a free flow of the tapped metal and slag, these must be maintained at least at 1600°C and 1700°C, respectively. This demands that the electrode temperature must be maintained at a reasonable level. It is apparent from the present analysis, that the electrode temperature cannot be decreased far below 2000°C in view of these requirements. Further, a reduction in the electrode temperature will reduce the production efficiency also. On the other hand, a temperature of 2500°C at the electrode can be considered to be the practical upper limit. A higher temperature can enhance the refractory wear and increase the load on the water cooling on the shell of the furnace. From the point of view of the quality of the hot metal, a higher electrode temperature is undesirable as this increases the size of the B-zone and enhances the silicon level in the hot metal.

It is apparent that the minimum level of silicon that can be achieved by controlling the electrode temperature is about 2%. Any further reduction has to be obtained by controlling the amount of silica passing through this zone. This has been analysed elsewhere ^[1]. However, a level of 2% of silicon in the hot metal may represent the lower limit for smooth operation of the furnace. Plant operators experience difficulties in tapping the metal at lower limits, due to reduced fluidity of the metal.

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