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MODELLING OF THERMAL PROFILE IN SUBMERGED-ARC FURNACE AND THE INFLUENCE OF COMPOSITION OF ORE ON THE THERMAL PROFILE

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ABSTRACT

The thermal state in submerged-arc furnaces (S.A.F.) producing ferro alloys is important for the conditions of both the grade of alloy produced as well as specific energy consumption. The temperature profile in the S.A.F. is affected by the endothermic chemical reactions and the rate of gas evolution . The gas evolution commences at about 900 C due to the reduction of iron in the ore. A first-principle-based 2-D model has been developed to predict the temperature profile in the furnace. In this study, four ores of different grades have been considered in order to simulate the thermal profile in the S.A.F. The influence of the composition of the ore on the thermal profile and its significance in rationalisation of charge distribution to optimise the process are discussed.

1. PRODUCTION OF FERRO-CHROME IN S.A.F.

The submerged-arc furnace has been the work horse for the production of ferro alloys, for many decades. It is a fairly energy-efficient furnace and is employed for tonnage-production of ferro manganese, ferro silicon, silico-manganese, ferro chromium etc. Three phase power supply is introduced in the process through three electrodes in a cylindrical refractory-lined steel shell. A schematic diagram of the submerged arc furnace can be seen in literature[1]. The charge which consists of a mixture of ores, coke and flux is heated by electric power supplied through carbon electrodes. The dimensions of the furnace considered for predicting the thermal profile are given in Table 1. Table 2 provides information on the major operating parameters. As the charge moves through the furnace, the oxides are reduced to iron and chromium and subsequently to the carbides. Whereas iron is produced at relatively low temperatures, starting at 900 °C, production of chromium requires higher temperatures, above 1200 °C, typically. Models to predict the temperature profile inside the SAF have been developed[2,3]. The kinetics of reduction of chromite ores with carbon has been studied by several authors.[4-10]. From these studies, it is possible to estimate the extent of reduction at different temperatures and different intervals of time. It was assumed that these estimates derived on the basis of experiments in the laboratory would be valid for the process inside the SAF also. Therefore, the heat required for the various reduction reaction along the axial and radial directions of the furnace could be estimated using thermodynamic data available in literature[11,12].

Table 1 : Major dimensions of the submerged arc furnace(mm) [1]

1. Diameter of the hearth	- 7910
2. Diameter of the top	- 8860
3. Height from the top of the charge bed to the hearth level	- 3190
4. Diameter of the electrode	- 1350
5. Pitch circle diameter of the electrodes	- 3290
6. Thickness of the refractory at the bottom	
(a) Carbon Blocks	- 800
(b) Magnesia castable	- 500
7. Thickness of the refractory at the side walls	
(a) carbon blocks	- 750

(b) Alumina castable - 100
8. Distance from the tip of the electrode to the hearth - 1100

Table 2: Operational data of the S.A.F used in the thermal profile model [1]

1. Temperature at the bottom of the hearth (on the shell) below the electrodes - 85 ^oC
2. Inlet temperature of the cooling wa - 25 ^oC
3. Outlet temperature of the cooling water - 34 ^oC
4. Flow rate of water - 400 m^3/h

(cooling around the steel shell of the furnace from a level of 0.5 m from the top).

2. DESCRIPTION OF THE TEMPERATURE PROFILE MODEL

The temperature profile in the S.A.F was simulated based on the following considerations[1]:

a) Plug flow of charge descent in the furnace. Radial or inclined movement of lumps or fines was not considered.
b) Channelling of gases, was not considered.
c) Heat generation due to combustion of gases above the charge bed was neglected.
d) Charge was assumed not to sinter inside the furnace.
e) Decrepitation of charge-constituents due to chemical and physical processes was neglected.
f) Thermo-physical properties of charge materials were taken to be functions of temperature.
g) Heat transfer co-efficient along the height of the furnace wall was assumed to be constant.
h) Temperatures measured at the bottom of the electrodes were used to evaluate the heat flux through the furnace bottom.
i) A two-dimensional single electrode system was assumed in the place of a three-dimensional three electrode industrial situation.

The thermal profile inside the S..A.F. is influenced by the interaction between the solid particles moving in the direction of gravity and gases such as CO and CO_2 moving in the opposite direction. The gases are generated by the reactions between the solid oxides in the ore and the coke in the charge material. The gases are heated by the heat dissiptaed in the arc region and in the liquid slag and metal due to resistance heating. The gases carry the heat to the upper regions of the furnace and pre-heat the descending charges. Then endothermic reduction reactions consume heat. The heat required for these reactions and the heat carried away by the top gas are two prominent factors that determine the temperature distribution in the furnace.

3. MATHEMATICAL MODEL

Mass and energy transport for the solid and gaseous phases were described by [1]:

$$C_{pi}\, G_i.dT/dZ = d/dZ(KdT/dz) + 1/r[d/dr(KdT/dr)] + S_i \tag{1}$$

$$(C_{pi}G_i)\,/dZ = dT\ ah(T_g\text{-}T_{ch}) \tag{2}$$

With the boundary conditions:

$dT/dr = 0$ along furnace centre line

$K_i dT/dr = q_1$ at furnace wall.

$K_b\, dT/dz = q_2$ at furnace bottom.

$K_{el}(dT/dr)_{el}=K_{ch}(dT/dr)_{ch}$ at charge-electrode interface.

where ‘i’ stands for the respective solid and liquid phases and 'g' for the gaseous phase. K,C_p and G represent thermal conductivity, specific heat at constant pressure and mass flow rate respectively.

$$a = 6(1\text{-}\varepsilon)/d_p \tag{3}$$

where ε is the bed porosity and d_p is the average diameter of lumps in the charge.

The gas-solid heat transfer rate was determined as a function of Reynold's number, determined from the local gas flow rate using the Nusselt relation given in literature[13].

Ohmic(resistance) heating was estimated in the electrode and the slag metal systems using the relationship:

$$Q=[1/\sigma]\{|j|^2\} \tag{4}$$

where

$$|j| = (j_r^2+j_z^2)^{1/2} \tag{5}$$

j_r and j_z were estimated from proportionate conditions of axial and radial current densities[14]. σ is the electrical conductivity of the phase under consideration. The shallowness of the layers of slag and metal; good mixing between the two phases above the hearth region and strong magneto-hydrodynamic flow in the two phases facilitate the assumption of a continuous phase for estimating the relevant physical properties.

The endothermic reactions occurring in the S.A.F. form the major source of heat consumption. The heat consumption is different in the different regions of the furnace and is controlled by the kinetics of reduction of the chromite ore. The kinetics of reduction measured through experimental studies in the laboratory was assumed to be valid under the conditions prevailing inside the S.A.F. The total amount of gas generated in each region also was a function of the extent of reduction. The finite difference method was used to solve the simultaneous governing equations (1) and (2). A 60*60 node grid gave satisfactory accuracy.

4. RESULTS AND DISCUSSION

The temperature profiles prevailing inside the S.A.F. for four different ores were constructed. The chemical compositions of the ores considered are given in Table 3. The temperature profile obtained in the cases of ores 1 and 2 are reproduced in Figures 1 and 2 for the sake of illustration. The temperature inside the S.A.F varied from about 250 °C at the top of the charge bed to about 2500 °C at the tip of the electrodes. The temperature increased in the axial direction towards the hearth from the top. It decreased away from the electrode region and closer to the walls of the furnace. Figures 1 and 2 show distinct differences in the temperature profiles. All the parameters used in the mapping of the temperature profile were kept constant in the two cases. Only the chemistry of the ore used in the process differed. The overall charge composition used in generating the profiles is given in Table 4.

Table 3: Composition of the four ores considered (mass%)

Ore	Cr_2O_3	Fe	MgO	Al_2O_3	CaO	SiO_2
A	31.75	8.169	22.33	6.25	2.52	23.10
B	43.5	10.28	10.88	12.39	0.34	17.56
C	43.0	14.43	6.98	13.53	0.36	5.31
D	37.03	7.578	17.58	4.04	1.44	10.97

Table 4: Composition of the charge (in tonnes/day)

1. Ore	294
2. Quartzite	68
3. Coke	33

The location of the isotherm 1750 °C was considered to examine the influence of the composition of the ore on the thermal profile. Table 5 gives the location of the terminus of the profile on the hearth as the distance from the centre of the furnace, in the four cases considered. Comparing this table with Table 3, it is found that

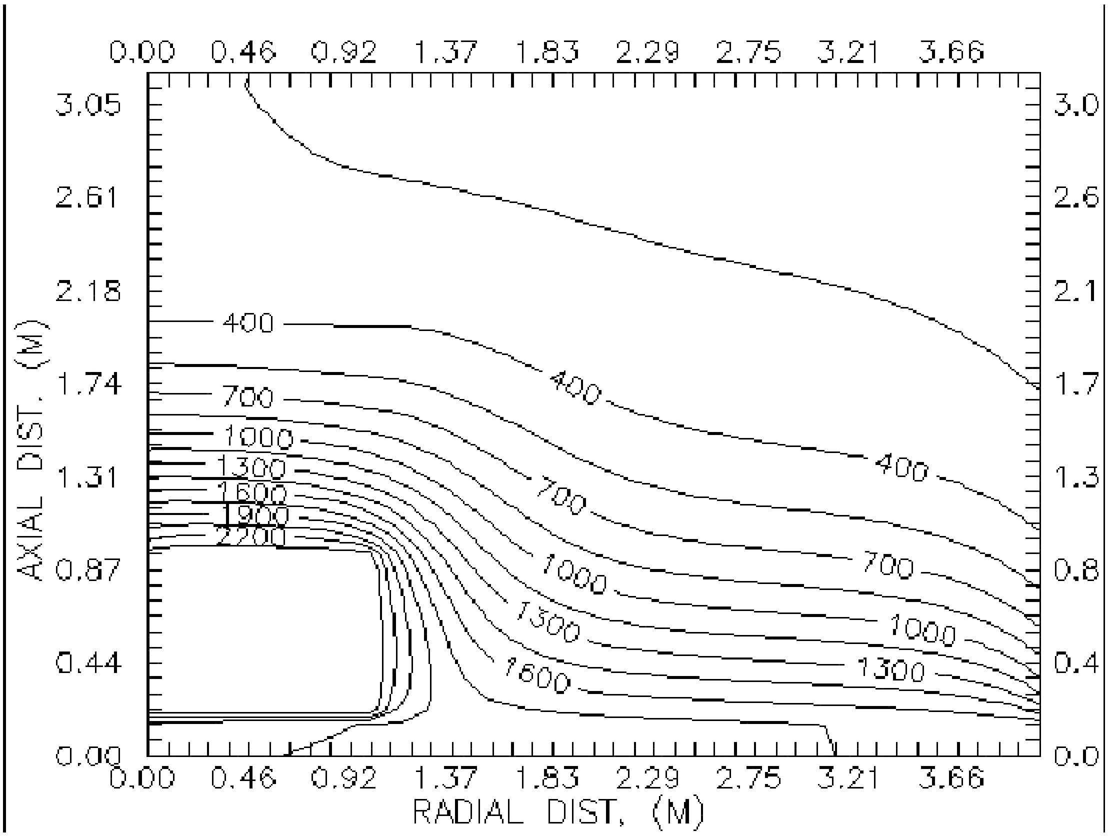

Figure 1: Temperature profile inside a submerged-arc furnace charging ore A

the location of the terminus is a function of the percentage of Cr_2O_3 in the ore. Higher is the chromium oxide content of the ore, closer is the location of the terminus to the center of the furnace. This distance is plotted as a function of $\%Cr_2O_3$ in Figure 3. It is found that the distance between the centre of the furnace and the terminus of the isotherm can be expressed as a logarithmic function of the level of chromium oxide in the ore expressed as mass percent. Higher is the level of Cr_2O_3 in the ore, higher is the heat required for the reduction of this oxide. Therefore, less heat is available for heating the slag and metal at the hearth level to higher temperatures. Therefore, the isotherm is restricted closer to the center of the furnace. This isotherm plays an important role in the smooth operation of the furnace since it represents the average temperature at which the slag is tapped from the furnace. If this isotherm does not extend closer to the wall of the furnace, it is possible that a solid skull is formed near the wall and the tap-hole and the tapping of slag is hindered.

The location of the terminus of the 400 °C isotherm along the vertical wall of the furnace was considered. This terminus was located at 1.09, 1.03, 1.02 and 1.09 m, respectively, from the hearth when the four ores were used as feed materials. This trend is caused by the higher amount of heat required for the endothermic reduction reactions. With a higher level of Cr_2O_3 in the ore, more heat is required. Therefore, the isotherm gets shifted towards the hearth. A reversal of this trend is noticed when the 250 °C, isotherm is considered. In this case, on moving from Ore A to Ore D, the terminus shifts from 1.67 m to 1.74 m from the hearth. It remains almost at the same level subsequently. With an increase in the amount of reducible oxides in the ore, the amount of gas generated increases. The gas serves to pre-heat the charge descending through the furnace. Therefore, the isotherm gets shifted towards the top of the charge bed. At this isotherm, the effect of endothermic heat requirement is not prominent since the reduction reactions effectively take place at locations far below this isotherm in the S.A.F.

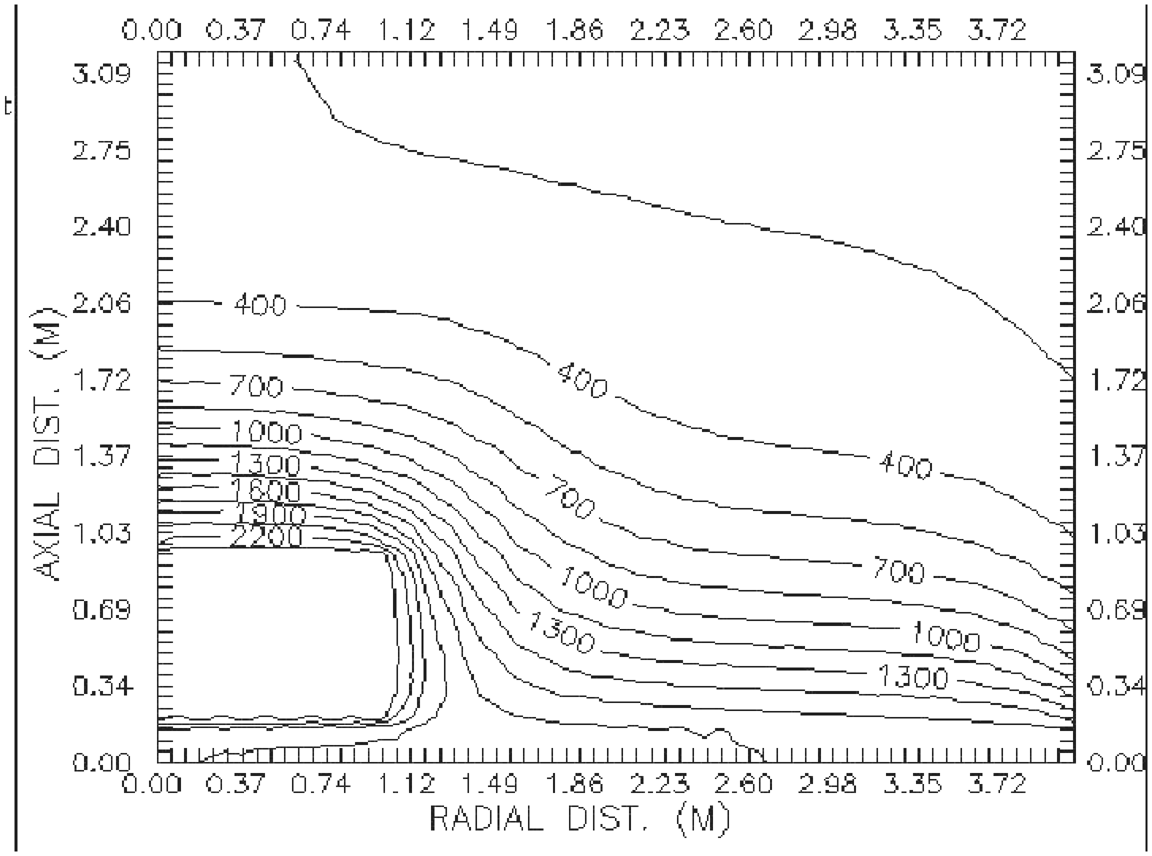

Figure 2: Temperature profile of submerged-arc furnace charging ore B

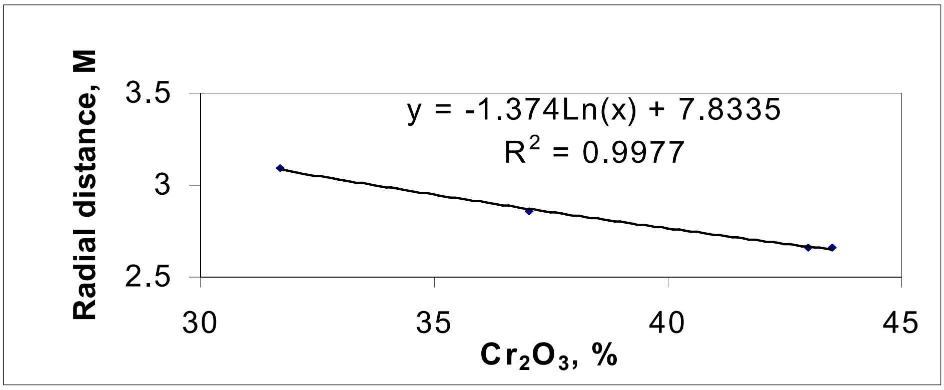

Figure 3: Influence o Figure 3: Influence of level of Cr2O3 in the ore on the location of the 1750 °C

In practice, the ferro alloy producers use a blend of different grades of ores in the S.A.F. Seldom is a singe ore used in the production process. The discussion above shows that different ores can generate different thermal profiles. A rationalised distribution of the different ores and other associated charge materials on the top of the charge bed would help in obtaining the optimum thermal profile to ensure optimisation of energy consumption and maximum recovery of metallic values.

Table 5: Location of terminus of 1750 ×C isotherm from the centre of S.A.F.

Ore	Location, m
A	3.09
B	2.66
C	2.66
D	2.86

5. CONCLUSION

Mode-based simulations were conducted to predict the thermal profiles in submerged-arc furnace producing ferro chromium. Four ores of varying composition were used in the simulations. The Cr2O3 content of the ores varied from about 31% to about 43%. It was found that the thermal profile varied with the composition of the ore. The 1750°C isotherm, which approximates the liquidus temperature of the slag was correlated with the Cr_2O_3-content of ore. A logarithmic relationship was obtained between the Cr_2O_3-content of the ore and the location of the terminus of the isotherm at the base of the hearth. This location was found to be farther from the centre of the furnace for the ores containing less Cr_2O_3. It was found that the generation of gases, due to reduction reactions, influenced the location of the isotherms at lower temperatures. These were shifted towards the top of the furnace, with an increase in the generation of gases. Optimised charge distribution will help in optimising the thermal profile and improving the efficiency of the process.

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