SIMULATION OF THE PRODUCTION OF FERRO-CHROMIUM IN SUBMERGED-ARC FURNACE

S. Rangnathan[1], K. M. Godiwalla[1], N. V. Satyanarayana[2] , Parvesh Kumar[1], Vardhan Rao[3],
A.K.Roy[3], B.Srikant[3]

[1] National Metallurgical Laboratory, Council of Scientific and Industrial Research, Jamshepdur 831 007, India
[2] Indian Institute of Chemical Technology, Hyderabad, India
[3] Navabahrat Ventures Ltd., Orissa, India, sriranga@nmlindia.org

ABSTRACT

Enhancing the process-efficiency in the production of ferro-chromium is crucial for the profitable production of this alloy in the submerged-arc furnace. Optimization of the specific power consumption and maximizing the recovery of metallics are the major goals of operators as well as researchers. A tool that can simulate the process offline under various conditions is required for achieving these objectives under varying conditions of raw material availability and adopt the appropriate operation practice. The simulation will also help in experimenting with the major operational parameters and optimising them before implementation in the process. This reduces the cost and effort required in devising improved operation procedures. A simulator has been developed to predict the influence of various operation parameters on the efficiency of the process. It contains three major modules (a) thermo-chemistry; (b) temperature profile and (c) electrical characteristics. The simulator has been validated using data from an industrial operation. It can be adopted in existing operations for enhancing the efficiency of production of ferro-chromium in the submerged-arc furnace.

1 INTRODUCTION

Ferroalloys constitute a vital ingredient in steel-making worldwide. The workhorse for production of these alloys from ores has been the submerged arc furnace, SAF. Charge materials include ore, briquette, sinter, pellets, metallurgical coke and fluxes such as quartz, limestone and dolomite. Fundamental studies on the kinetics and thermodynamics of the smelting process as well as those of the electrical characteristics have been dealt with in literature[1–16]. In the SAF several multiphase phenomena occur in various regions of the furnace. It is now clear, both from plant practice and theoretical analysis that location of specific raw materials in the SAF charging system plays a crucial role in obtaining a quality product[13]. Heat is generated essentially in the arc-zone of the furnace. In addition to this, ohmic heat is generated when current passes through the semi-molten charge. The efficiency of the process depends on a proper balance between the heat generation, heat lost as sensible heat through the metal, slag and gas; temperature of the refractory near the walls; the degree of reduction at different levels; thermodynamic equilibrium between metal and slag. Therefore, several thermo-physical and thermo-chemical phenomena interact in determining the efficiency of the process. The operator must be able to predict the influence of various operation parameters on the efficiency of the process so that he can ensure attainment of maximum efficiency possible. Hence, an off line simulator was developed as a first step to address this problem, in the manufacture of ferro-chromium. The simulator essentially has three modules, each for a specific function describing the SAF operation in ferroalloy industry. Details of these modules is described in the text to follow.

2 THERMO-CHEMICAL MODULE

2.1 Scope

Various types of chromite ores are used in the manufacture of ferro-chromium. These ores various oxide species such as Cr_2O_3, FeO, Fe_2O_3, Al_2O_3, SiO_2, MgO and CaO. The choice of the ore depends on the availability, cost and the need to maintain optimum ratios of various oxides in the charge mix.

Quartz or Quartzite is commonly used as flux. This serves to reduce the melting temperature of the slag. Carbon in the form of coke or anthracite is used as the reducing agent. Energy is required for the reduction of the oxides and for melting the slag and metal. In addition to these processes, the top gas carries away energy as sensible heat. Heat is also lost through the walls of the furnace and the electrode-cooling system. The simulator must meet the following requirements: (1) Estimate the mass ratio of critical oxide species in the total charge; (2) Estimate the ratio of total chromium to iron in the charge; (3) Predict the quantity of metal produced for the given charge composition; (4) Predict the composition of the metal produced; (5) Predict the total slag produced for the given charge composition; (6) Predict the composition of the slag; (7) Predict the heat required for the reduction reactions; (8) Predict the heat required for melting the metal; (9) Predict the heat required for melting the slag; (10) Predict the sensible heat of metal; (11) Predict the sensible heat of slag; (12) Estimate the heat carried by the gas; (13) Estimate the heat lost through the gas phase; (14) Predict the magnitudes of the various parameters for change in the quantities of various charge materials.

2.2 Data Input

The data input to the first screen of the simulator would consist of the weights of various ores charged; the weights of fluxes charged and the weights of cokes charged. In addition to the weights, the chemical composition of each of the charge material in terms of wt% of the various oxide species and carbon must be entered. There is provision for entering data for up to six ore species; one flux and four coke species. However, these names are interchangeable. For example, it is possible to enter data on coke under the title "ore" and vice versa. The design of the screen is flexible to accommodate these changes. This ensures that the same screen can be used for various circumstances. This simulator has two major modules: (a) Thermo-chemistry and (b) Kinetics of reduction. The user can access each of the modules independent of the other.

2.3 Thermo-chemistry Module

This module gives the total weight of the charge materials taken, in the form of ores, fluxes etc. It gives the Al_2O_3/MgO and the Cr/Fe ratios in the charge. The user can alter the weights of various charge materials to obtain the desired ratios. The "*estimate*" screen estimates the metal production accurately. The data *input* required for this screen are the wt%MgO and wt%Cr_2O_3 in the slag in addition to the wt%Cr, wt%Si and wt%C in the metal. These are average values for the day's production corresponding to the charge entered in. The "*energy*" screen estimates the heats required for the various processes occurring inside the furnace. This screen gives information on the heats required for the reduction reactions; for the melting and heating the metal to 1600 °C and for the melting and heating of slag to its liquidus temperature. This screen also displays the liquidus temperature of the slag estimated from its chemical composition. The estimate made by the simulator is within 7 °C error band for the compositions of slags normally encountered in the production of ferro-chromium.

2.4 Kinetics Module

This screen collects data on time, temperature, particle sizes of ore and coke from the user. It provides information on the degree of reduction of iron and chromium for the given time interval and the temperature chosen for the given particle size of ore and coke. The estimates are based on the kinetics of reduction of the ore. This is sensitive to the nature of the ore. In all the screens the data entered can be saved against the date of entry and retrieved at any later date. These data can be retrieved for further analysis on any occasion.

2.5 Using the Module in Industrial Operation

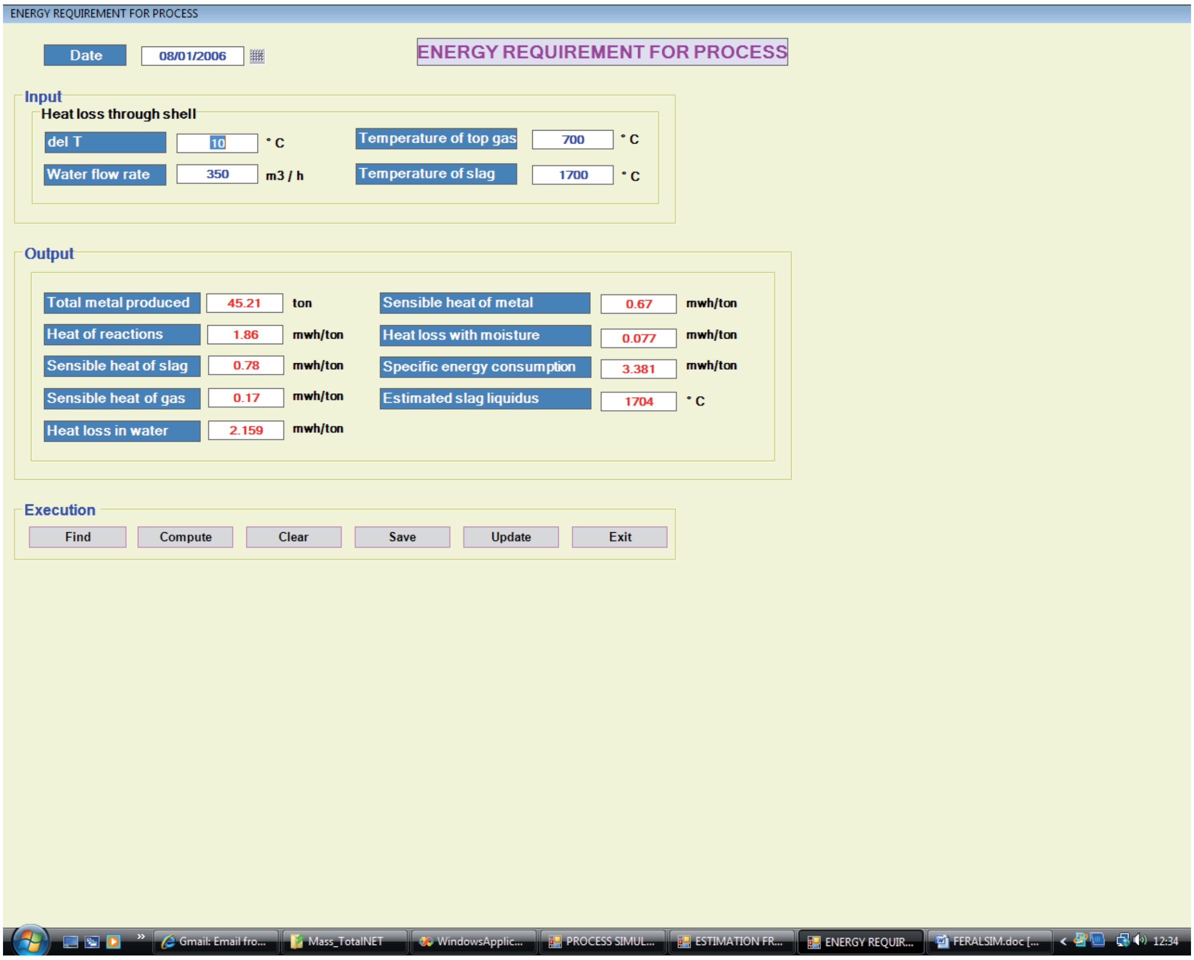
1. The weights of various charges can be optimized to obtain the desired ratios of Al_2O_3/MgO and Cr/Fe in the charge. The decision can be based on the availability of charge materials on the given day.
2. A highly accurate estimate of the metal production can be obtained. The predictions are within an error of 1%, when data are logged carefully. The predicted mass of slag produced and its chemical composition obtained are also highly reliable. The user can apply information form this screen for improving the operation in the following ways:

(a) Use the data on the recovery of chromium to improve the process and enhance the recovery further.
(b) Use information on the metal production to maintain reliable inventory of

(c) Use the information on the size of the high temperature zone to regulate the operation. The size of this zone must be optimum. Higher the size, higher is the reduction of SiO_2 and higher is the specific power consumption. If the size is less than the optimum, there will be improper distribution of temperature leading to problems in operation as well reduced recovery of metallics.

3. The '*energy*' screen tells how the energy supplied to the furnace is utilized. This, in turn, will help in devising strategies to reduce the wasteful expenditure of energy. An important aspect of energy loss is the heat lost through the slag as sensible heat. This depends essentially on the liquidus temperature of the slag. Analysis of data from industry has shown that there is a huge variation in this temperature leading to an enormous wastage of energy. This screen gives a reliable estimate of the liquidus temperature. Using this, the operator can fine-tune the composition of the slag, so that the liquidus is controlled within a narrow limit. This will considerably reduce the specific energy consumption. Heat loss through the gas is another source of loss which can be minimized using this module. This can be achieved using the modules on 'reduction kinetics' and on the 'temperature profile', along with the '*energy*' screen. Another important contribution by this module is helping the operator to schedule the tapping. When the operator is aware how much of energy is actually required per tonne of hot metal, he can schedule the tapping with good precision, leading to considerable saving in energy. A screen shot of the '*energy*' screen is given in fig. 1.

4. The module on the '*reduction kinetics*' will be useful for the operator to estimate the total time required for reduction reactions to be completed and optimally schedule the tapping of metal based on this information. This can avoid premature tapping leading to losses in slags or over-heating of the metal which will drain energy without proportionate increase in production.



Date 08/01/2006

Input

Heat loss through shell

del T 10 ° C
Water flow rate 350 m3 / h
Temperature of top gas 700 ° C
Temperature of slag 1700 ° C

Output

Total metal produced 45.21 ton
Heat of reactions 1.86 mwh/ton
Sensible heat of slag 0.78 mwh/ton
Sensible heat of gas 0.17 mwh/ton
Heat loss in water 2.159 mwh/ton
Sensible heat of metal 0.67 mwh/ton
Heat loss with moisture 0.077 mwh/ton
Specific energy consumption 3.381 mwh/ton
Estimated slag liquidus 1704 ° C

Figure 1: The "Energy" screen of the Simulator.

3 TEMPERATURE PROFILE MODEL AND SIMULATION

3.1 Scope

Optimum temperature profile of the furnace is crucial for the successful operation of the process. Temperatures at the hearth and tap hole region must be above the liquidus temperature of the metal and that of the slag so that these liquids do not freeze and tapping is smooth. The temperature distribution must be symmetric in the furnace along the radial direction. The top of the charge bed must be at an optimum temperature so that the heat loss through radiation and convection is minimized. The heat carried away by the top gas also should be minimum. The temperature distribution must be such that the charge gets adequate time to get reduced as it travels down the furnace to the hearth region. This will have an impact on the scheduling of metal tapping for maximising efficiency of operation. The '*Temperature Profile*' Module must be capable of providing the following crucial information: (1) Temperature of the metal and slag at the hearth level: (2) Temperature at the slag port; (3) Size of the high temperature zone: (4) Sizes of various temperature zones: (5) Temperature at the op of the charge bed: (6) Temperature along the walls

3.2 Factors Influencing the Temperature Profile

The following factors influence the temperature profile inside the furnace:

1. Heat generation through ohmic heating in the various zones
2. Temperature at the electrodes
3. Heat capacities of charge materials, metal, slag.
4. Thermal conductivity of charge materials
5. Heat requirement for reduction reactions and melting
6. Porosity of the bed which is influenced by the particle size, shape etc.
7. Quantity of gas generated and its heat capacity
8. Thermal conductivity of refractory
9. Heat loss through radiation at the top of the charge bed

The modelling of the temperature profile in the submerged-arc furnace has been already discussed in detail elsewhere[14]

3.3 Using the Module in Industrial Operation

This module is a highly valuable tool for understanding the operation and controlling it.

1. Combined with the module on '*reduction kinetics*', this module will give an estimate of the time required for the complete reduction of chromium and iron. This can be used for scheduling the tapping of metal and slag.
2. The module can be used for adjusting factors such as bed porosity to generate an ideal temperature profile that can minimise the heat loss through the walls.
3. This module will give an estimate of the high temperature zone. This can be controlled through appropriate modification in operation practice, such as applied voltage, charge distribution on the top of the bed etc.
4. This module will serve to explore the influence of altered charge distribution on the top of the bed and develop new operation practices.
5. This module can be used for controlling the temperature of the top gas and reduce the loss through this.

Figure 2 gives a typical temperature profile in a submerged-arc furnace.

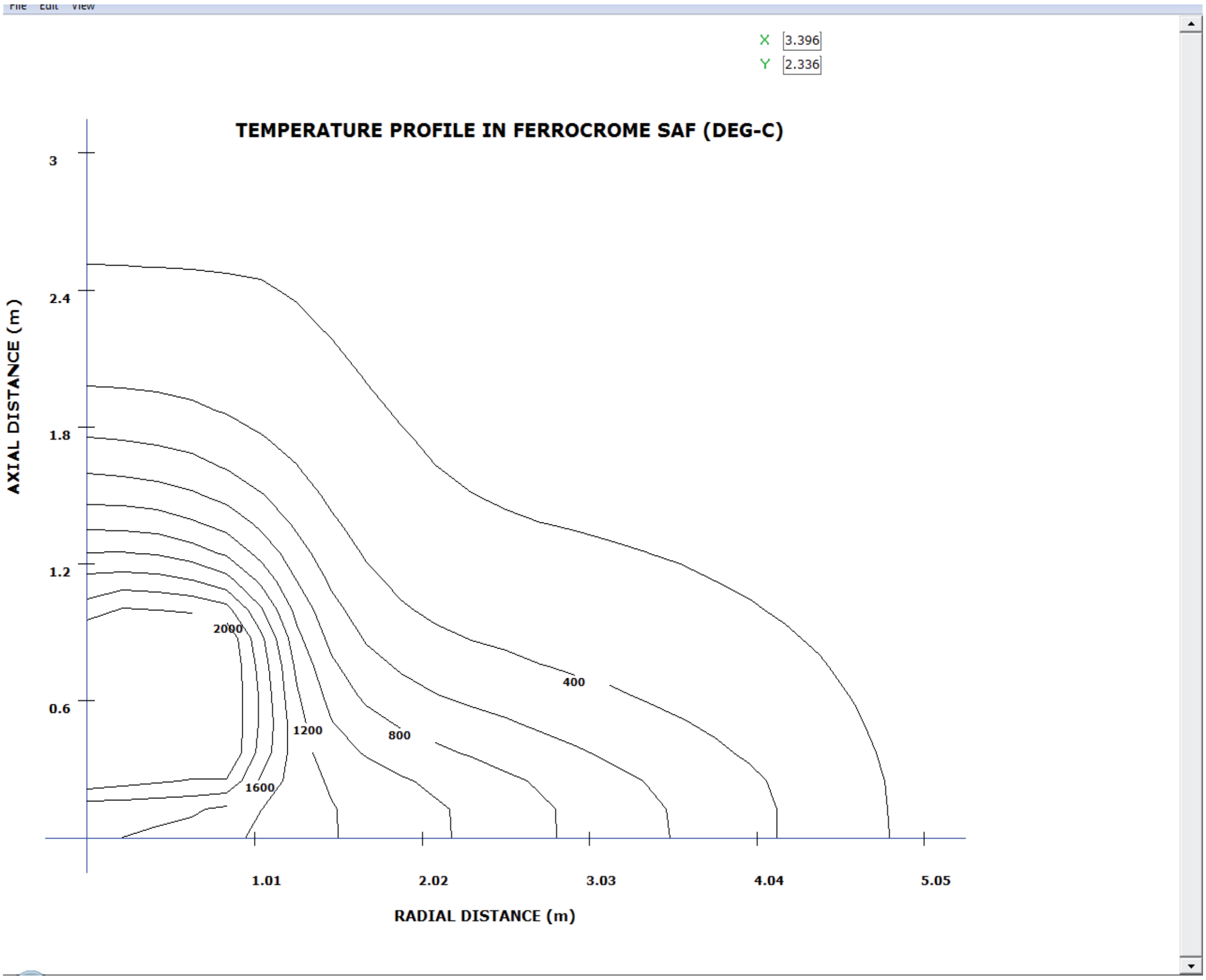


Figure 2: Predicted Temperature profile in the Submerged-Arc Furnace.

4 SIMULATION OF ELECTRICAL CHARACTERISTICS

4.1 Scope

The data available from the furnace operation on the electrical parameters are the primary voltage of the transformer, the primary current and transformer ratio. From these, the other relevant parameters have to be estimated. This module can provide: (1) Estimated secondary voltage across each electrode: (2) Estimated secondary current through each electrode; (3) Resistance of the arc medium; (4) Current density below each electrode; (5) Power density below each electrode; (6) Monitoring of electrical parameters at intervals of ten minutes; (7) Monitoring of the data every hour

4.2 Process Requirements

The power distribution through the three electrodes must be uniform for ideal operation. The power distribution and current distribution along the axial and radial directions must be such that these distributions are uniform and are at the optimum level for maximum efficiency of operation. Non-uniform distribution will lead to uneven charge descent; excessive erosion of refractory in some regions; accumulation of un-reacted material in some regions; inefficient utilisation of furnace volume; excessive erosion of electrode(s). Monitoring of arc resistance is vital for controlling the process. Ideally, the resistance must be maintained constant throughout the operation, after allowing for changes during tapping of metal and subsequent build-up of charge under the electrodes. Modelling the electrical characteristics are discussed in detail elsewhere[17].

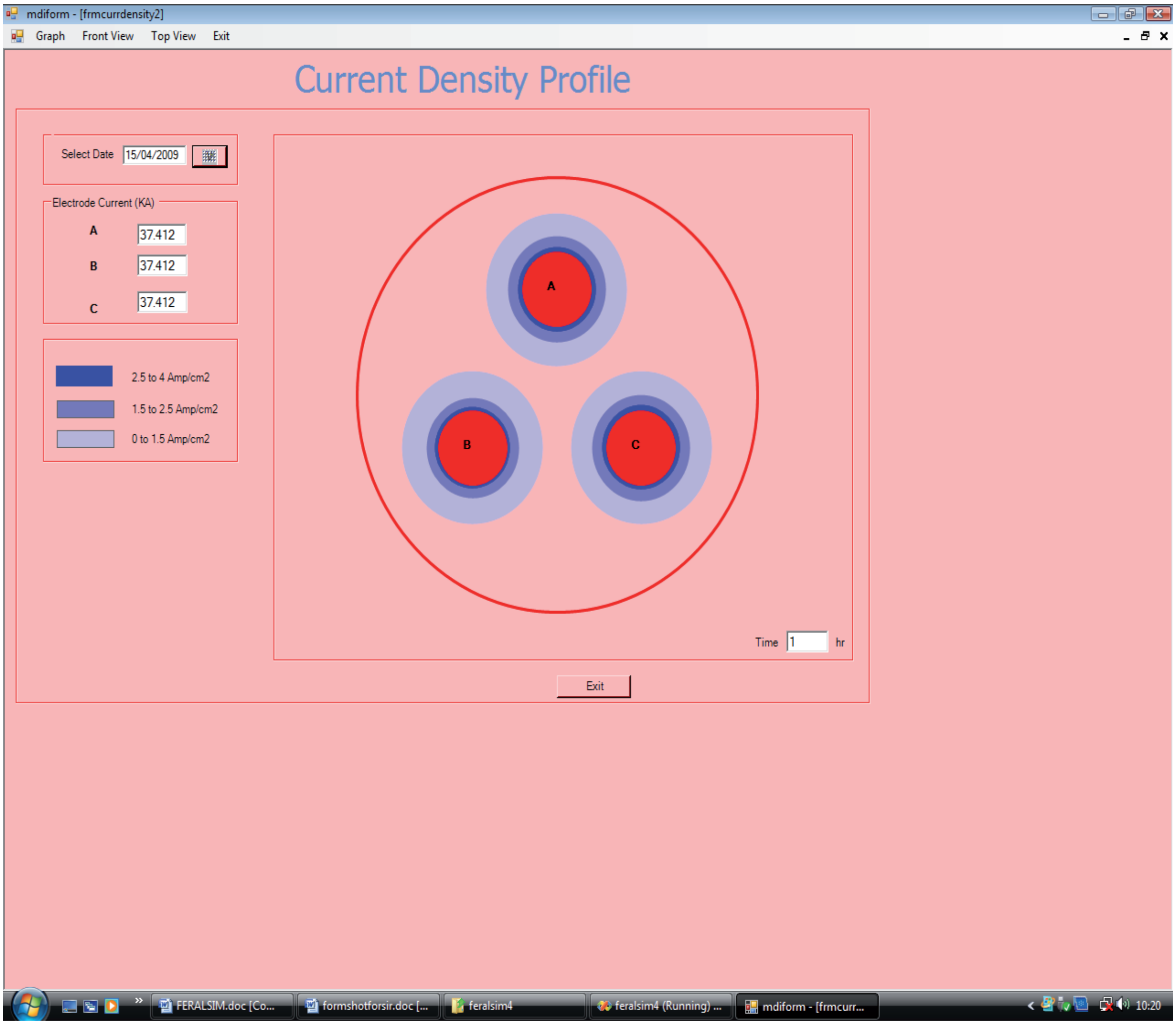
4.3 Determination of Current-density and Power-density Profiles

The SAF typically operates in the current range 1.5 to 4.7 A/cm$^{2.}$ The operation characteristics of the process depends on the resistance. The resistance depends on arcing, carbon balance and the electrode-to-bath distance. These factors must be controlled in the operation of SAF. Consistent with the restrictions on the distribution of power within a furnace and the limitations on electrode resistance, factors such as inter electrode spacing, furnace internal diameter and depth can be calculated. From a knowledge of the secondary voltage and current, the current density and power density under the electrodes are predicted.

4.4 Using the Module in Industrial Operation

The module can be used in controlling the operation through the following strategies:
1. Monitoring the secondary current and voltage at short time intervals and taking corrective action to maintain balance of power supply among the three electrodes
2. Maintaining appropriate secondary voltage and current among the electrodes
3. Maintaining the optimum arc-resistance
4. Maintaining the optimum power density and current density profiles.

Figures 3 and 4 represent the current and power densities estimated for an industrial furnace.



Current Density Profile

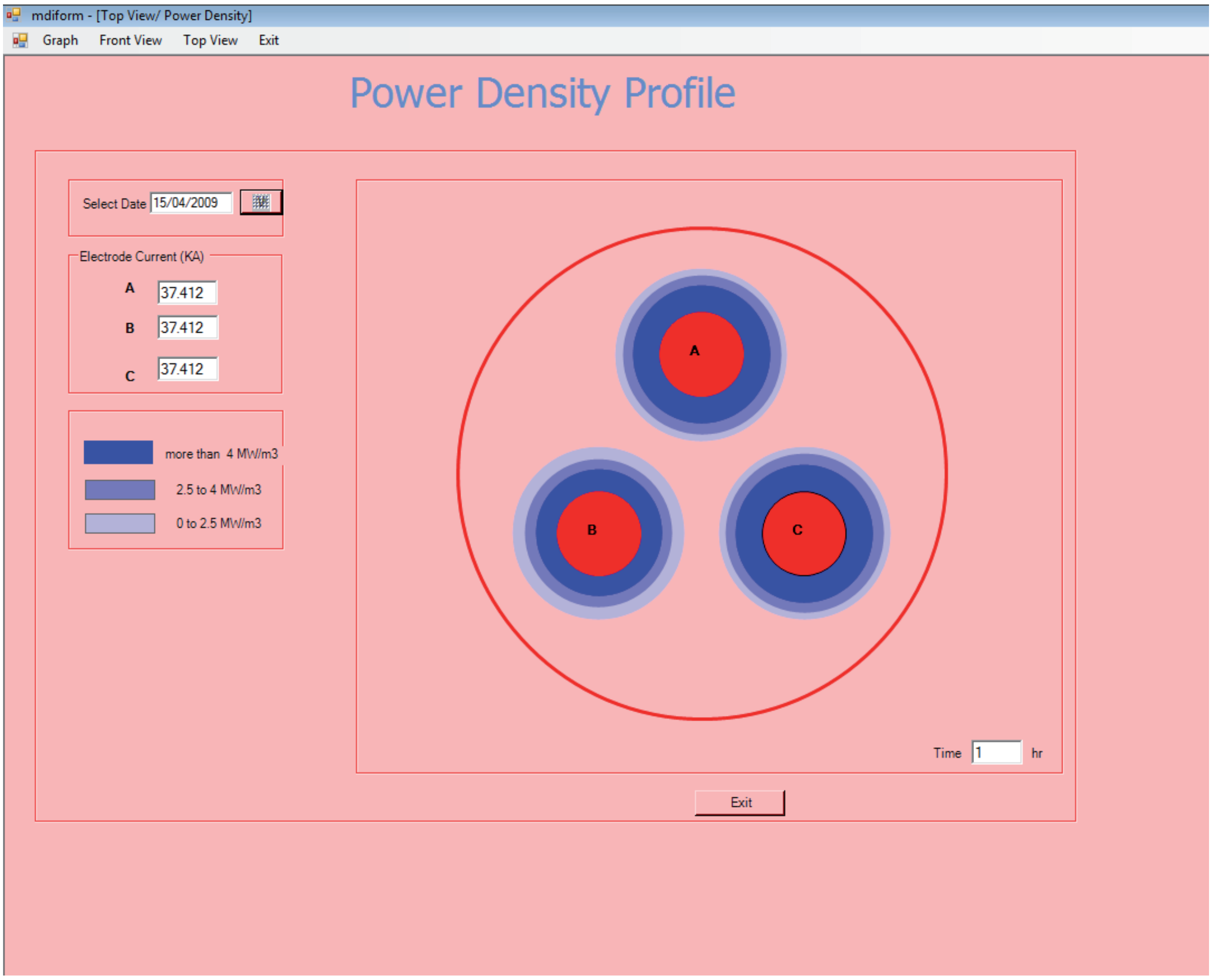
Select Date 15/04/2009

Electrode Current (KA)
A 37.412
B 37.412
C 37.412

■	2.5 to 4 Amp/cm2
■	1.5 to 2.5 Amp/cm2
■	0 to 1.5 Amp/cm2

Time 1 hr

Figure 3: The Current Density profile of a Submerged-Arc Furnace Around the Electrodes.



Power Density Profile

Select Date 15/04/2009

Electrode Current (KA)
A 37.412
B 37.412
C 37.412

Time 1 hr

Figure 4: The Power Density Profile of a Submerged-Arc Furnace Around the Electrodes.

5 VALIDATION

Data were collected from industries to validate the simulator. Figure 5 compares the quantity of metal produced predicted by the simulator with that reported by the Plant. Though there is scatter in either direction, the two sets of data agree with each other with an average deviation of 1.65%. Similar agreement is seen between the sets of data with respect to the composition of the slag as well as the heat required for the process as demonstrated in figures 6 and 7. Considering the considerable difficulty in generating dat with high accuracy in industrial operation, the agreement between the values predicted by the simulator and the data reported by the plant is considered to be excellent.

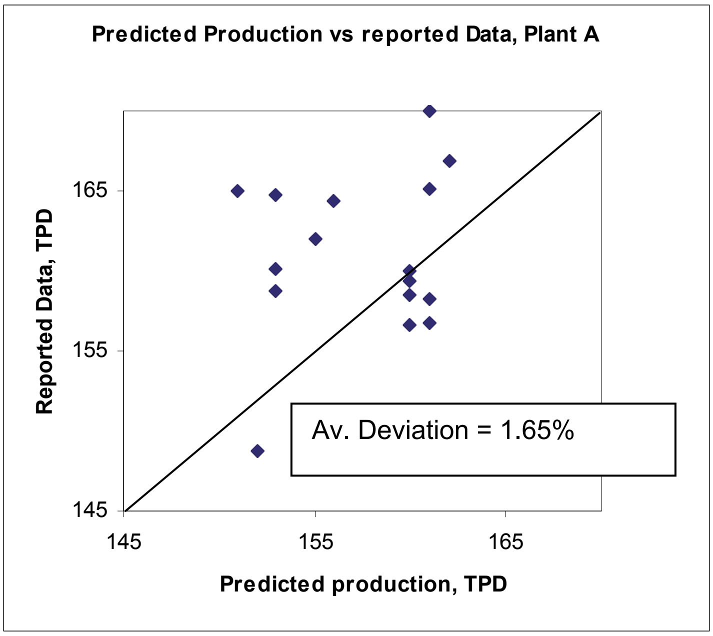


Figure 5: Predicted production compared with Plant data.

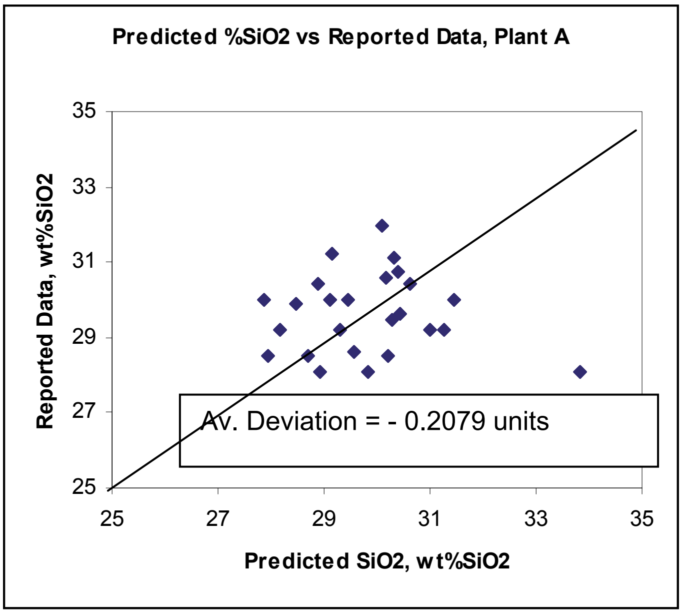


Figure 6: Predicted slag composition compared with Plant data.

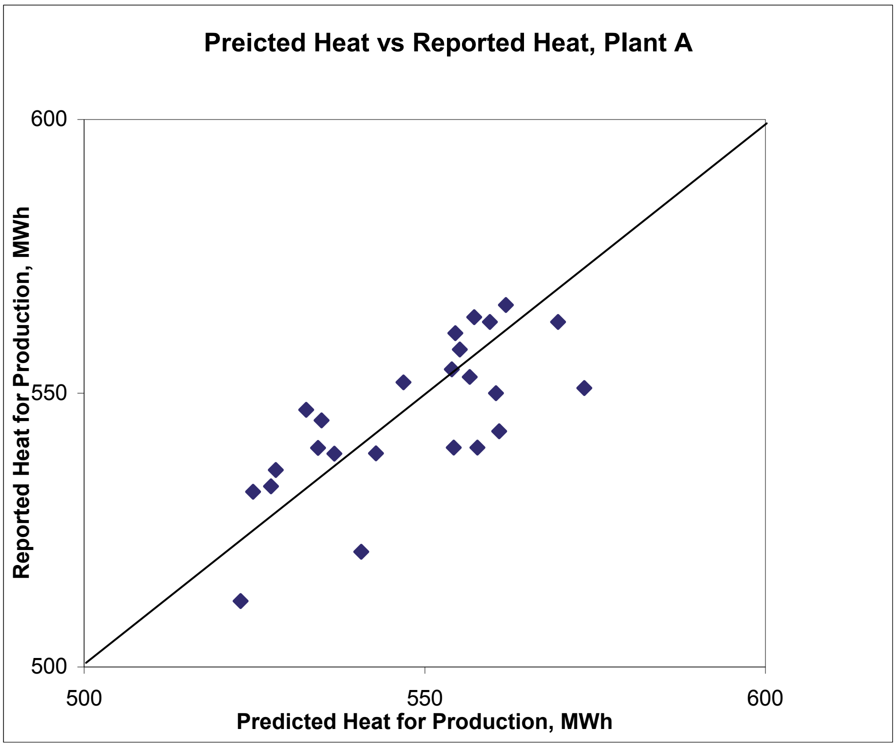


Figure 7: Predicted heat requirement compared with plant data.

6 SUMMARY

A simulator has been developed for predicting the performance of the process during the production of ferro-chromium in submerged-arc furnace under various operation conditions. The simulator predicts the thermo-chemistry, the temperature profile and the electrical characteristics of the process. This can be used for enhancing the efficiency of the process by maximising the recovery of metallics and optimising the energy consumption. The various features of the simulator and its application in industrial environment have been discussed. The modules have been named FERALSIM1, FERALSIM2 AND FERALSIM3. These are available for use by the industries to enhance the efficiency of their processes.

7 ACKNOWLEDGEMENT

The authors are grateful to the Department of Information Technology, Ministry of Communication and Information technology for financial support to carry out the investigations presented above.

8 REFERENCES

[1] J.Yonemochi, Innovations and Improvements in Metallurgical Processes – Ferro alloys -I, Electric Furnace Conference Proceedings, 1976, pp.73-84.
[2] M.S.Rennie, MINTEK ’50, Ed. L.F. Houghton, 2(1985), pp.777-785.
[3] J.Westly, Electric, Furnace Conference Proceedings, 1975, pp.47-53
[4] J.H. Downing and F.W.Leavitt, INFACON ’80, Second International Ferro Alloy Congress, Lusanne, Switzerland, 12-16 Oct. 1980, Institut des Producteurs de Ferro- Alliages d’Europe Occidentale, 20 ave. de la Gare, pp.83-107.
[5] G.Sommer, N.A. Barcza, I.J.Baker, M.S.Rennie, A.B.Stewart, INFACON ’80, Second International Ferro Alloy Congress, Lusanne, Switzerland, 12-16 Oct. 1980, Institut des Producteurs de Ferro-Alliages d’Europe Occidentale, 20 ave. de la Gare, pp.53-70
[6] B.O’Shoughassey and M.Sciaronne, INFACON ’80, Second International Ferro Alloy Congress, Lusanne, Switzerland, 12-16 Oct. 1980, Institut des Producteurs de Ferro-Alliages d’Europe Occidentale, 20 ave. de la Gare, pp.370-385.
[7] J.H.Downing and F.W.Leavitt, 36th Elec. Furnace Conf. Proceed., 1978, pp.209-216.

[8] S.Xu and W.Dai, INFACON 6, Proceed. 6th Intl. Ferro alloy Congress, Cape Town, Johannesburg, South African Institute of Mining and Metallurgy, 1992, pp.87-92.

[9] D. Neuschutz, INFACON 6, Proceed. 6th Intl. Ferro alloy Congress, Cape Town, Johannesburg, South African Institute of Mining and Metallurgy, 1992, pp.65-70.

[10] H.G.Vazarlis and A.Lekatou, Ironmaking and Steelmaking, 20(1993) 1, pp.42-53.

[11] A.Lekatou and R.D.walker, Ironmaking and Steelmaking,22(1995) 5, pp.378-392.

[12] Y.L.Ding and N.A.Warner, Ironmaking and Steelmaking, 24(1997) 3, pp.224-229.

[13] S.Ranganathan, Ironmaking and Stelmaking,25(1998) 6, pp.466-471.

[14] S.Ranganathan and K.M. Godiwalla, Steel research, 69(1998) 12, pp.476-481.

[15] George W. Healy, Electric Furnace Conference Proceedings, 1991, pp.251-258

[16] W.D.Heiss, “Modelling and simulation of electric smelting furnaces”, Iron making and Steelmaking, 9(1982) 5, pp.217- 221

[17] ‘Process Simulation for Optimisation of Ferro-Chrome Production in Submerged-Arc Furnace’, Internal Report, national Metallurgical laboratory, Jamshedpur, India.