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Modelling of A Dc-Arc Furnace Used for Smelting of Ferronickel Ore Fines

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Abstract

The use of DC arc furnace is considered today an attractive alternative for smelting of ores of many varieties. In this paper we present an approach for a thermal and electrical model of a DC arc furnace used for smelting of ore fines, experimental verification of model in a pilot furnace used for smelting of ferronickel ores, results obtained and conclusions.

The principal goal of this project is to offer to the engineers of smelting industry and our students an important tool for understanding the modeling techniques and the use of simulation software in the designing of DC arc furnaces used for smelting ore fines.

In the near future we shall present dedicated software for designing of DC arc furnaces for smelting of ore ferronickel fines which is under development and is based on models and the results presented here.

Keywords: DC arc furnace, modeling, FEM, smelting, ore fines

INTRODUCTION

DC arc furnaces have been in use in the metallurgical industry since the late 1800s in the field of steel scrap processing. But, recently, they have started gaining acceptance in the area of smelting of ores of many varieties, for example, the smelting of chromites to produce ferrochromium [1], ilmenite smelting to produce titania slag and pig iron [1], recovery of cobalt from non-ferrous smelter slag [2], treatment of stainless-steel plant dust [3], smelting of nickel laterite ore to produce ferronickel [4], production of platinum group metals [5], etc. Main advantages of DC-arc furnace technology for smelting of ores are:

- the ability to treat directly ore particles less than 1 mm in size, improving the overall recovery of metal without the need for expensive agglomeration techniques
- the CO-rich off-gas from the furnace could be used to supplement the energy requirements, and is also a good reducing agent
- effective control of the reductant addition, as there is no direct contact between the graphite electrode and the melt
- the ability to run at an optimum slag temperature, due to the open-bath mode of operation
- It is possible (and desirable) to maintain a layer of frozen material in contact with the sidewalls, in order to protect the refractory lining of the furnace [4]

Since 1995, in the department of electrical applications, in the Polytechnic University of Tirana, we have developed successfully a project for thermal and electrical modeling of different electrical furnaces [6,7]. Based on our previous experience, looking the increased inters of industry in Albania for DC arc furnaces used for smelting of ferronickel ores and with their support, we are developing recently a project for modeling of such furnaces.

Investigation in international literature and market has shown us, that there are a lot of efforts and excellent results in developing models and software in the field of electro metallurgical processes and especially for DC arc furnaces of various applications. Pilot DC arc furnaces used for smelting of ores has been tested at a number of world site locations and different models have been proposed [1, 2, 3, 8, 9, 10]. We have done our best to apply such result in our project, learn from their experience and improve our ideas.

In this paper we present an approach for a thermal and electrical model of a DC arc furnace, experimental verification of model in a pilot furnace for smelting of ferronickel ore fines, results obtained and conclusions.

The principal goal of this project is to offer to the engineers of smelting industry and our students an important tool for understanding the modeling techniques and the use of simulation software in the designing of DC arc furnaces used for smelting of ferronickel ore fines.

In the near future our objective is, that based on the existing results presented here, to develop dedicated software which shall compute a steady state distribution field of temperatures, heat losses, and electric power and shall enable the simulation of furnace behavior both numerically and/or graphically in response to process and operational changes, which can allow the user to specify:

- appropriate layout of furnace based on compromises between the requirement for low energy loss and a moderate thermal resistance
- appropriate selection of refractory material
- appropriate ranges of voltage and current for the power supply

Software shall offer an interactive environment allowing examining and comparing of any desired configuration of the furnace layout and electrical supply scheme with quick feedback. Step by step comparing process of different solutions, can guide the user in appropriate decisions which can satisfy different criteria selected by him, as low energy loss for example. We are working hard for compiling this software and believe that in a very near future shall be able to present it in a paper. As a matter of fact the simulation of thermal model and calculations presented here are done by modules of this software and controlled with licensed FEMLAB software.

MATERIALS AND METHODS

Furnace construction and operation

In general, the construction of a DC-arc furnace comprises a water-cooled refractory-lined cylindrical shell, a conical roof, a graphite electrode, and an anode. Figure 1 shows a typical schematic construction diagram of a DC arc furnace used for smelting of ferronickel ore fines. The electrode may be hollow, and the feed area of ores may be introduced through the hollow centre of the electrode.

A simplified schematic of furnace electrical supply is composed by a DC power supply, which is typically a bank of rectifiers connected to an AC transformer, and the furnace unit itself. The molten bath forms part of the electrical circuit (anode). The return electrode, or anode, consists of multiple steel rods built into the hearth refractories and connected at their lower end to a steel plate which via radial extending arms, is linked to the furnace shell, and further to the anode cable.

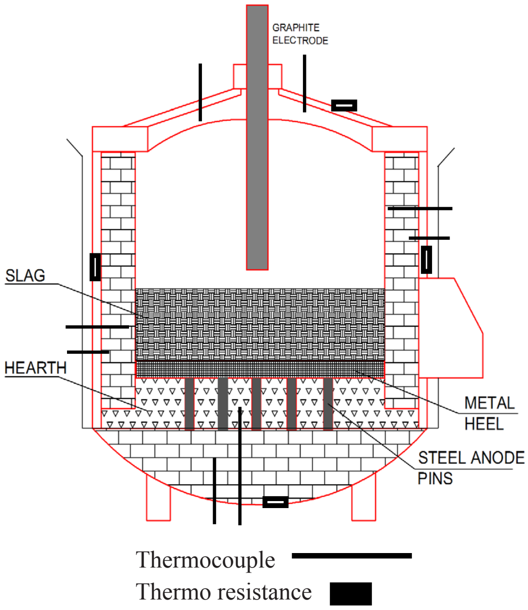

Figure 1. Schematic construction diagram of a DC arc furnace and the distribution of thermocouples and thermo resistances during experiment

The furnace is fed more or less continuously, and is tapped periodically (or even continuously, if so desired). The furnace is operated at a slightly higher pressure than that of the surrounding atmosphere, in order to substantially exclude the ingress of air into the furnace [4].

Thermal Modeling

The thermal analysis of DC arc furnace has conduct in creating of a two-dimensional finite element model (FEM) for typical cross section of the furnace. 2D FEM model is considered reasonably complete to understand steady state thermal behavior of the furnace for the prediction of field temperatures and heat losses in refractory-lined shell walls, roof, hearth and coolers. Simplifications are done to get an industrially relevant model. The temperature field is assumed to be uniform in all vertical cross sections of the furnace, and the edge effects in the direction perpendicular to the cross section are neglected. The furnace construction is assumed to be geometrically and thermally symmetric along the vertical furnace axe. Only conduction heat transfer is considered. Convective and

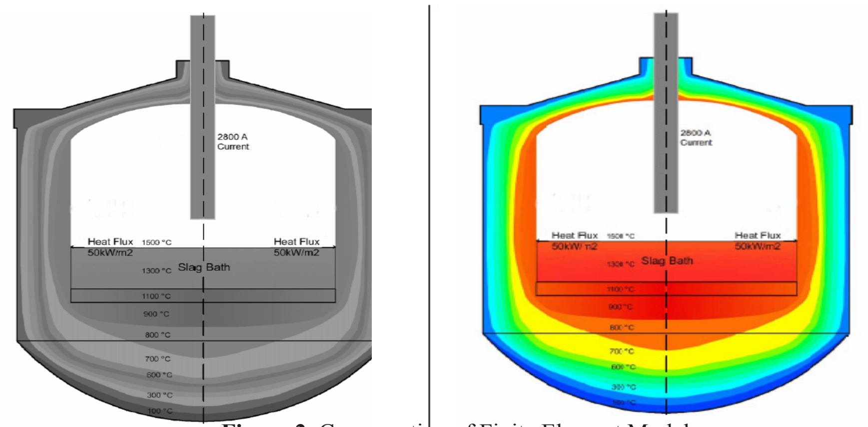

Figure 2. Cross section of Finite Element Model

Ps. In case that colored diagram can not be printed, the editor may use black and white version radiative heat losses are neglected. The contact between slag and furnace shell sidewalls, shell walls and coolers in our model considers only a heat balance. The thermo physical properties of the furnace shell and roof wall material are assumed to be temperature dependent, except the density. Mesh geometry, mathematical formulation and assumed linearity's provided in reference literature [7] are adapted.

In Figure 2 is presented a cross-section of 2D FEM of a 300kW DC pilot arc furnace with 2.5m internal diameter and 50 cm slag depth. It shows boundary conditions and temperature field layout. The results of figure 2 are based on boundary conditions which include a top of metal bath temperature of 1500°C, external shell plate temperature 100°C and a total current of 2800 A.

Electrical Modeling

The electrical system analysis and modeling of furnace has been done for understanding the electrical behavior of the furnace in response to process and operational changes, which can allow specifying appropriate ranges of voltage and current for the power supply. It is very important for the power supply of a furnace to be able to deliver power at the designed level; otherwise furnace throughput will be adversely affected. If the actual operating voltage is lower than anticipated, the power supply might be unable to deliver the current required for the intended power. On the other hand, if running a process with a highly resistive slag, the power supply needs to be able to operate at a sufficiently high voltage.

The total electrical load in a DC arc furnace consists of two loads in series, the first is the plasma arc column and the second is the slag bath. Modeling the electrical behavior of these two components allows the behavior of the furnace to be understood as a whole.

To have a reasonably complete description of the electrical behavior of the DC smelting arc furnace, the model provided in reference [8,9] is adapted. Bowman through an equation describes the radius of the conducting volume of the arc as a function of the distance from the cathode attachment spot. The assumptions include an axisymmetric arc and no interaction effects at the anode. Assuming a parabolic distribution of electrical conductivity along the arc's radius, the arc shape function allows the arc voltage to be obtained by integration. Several empirical constants of Bowman's, along with a single variable parameter and the average arc resistivity, appear in the arc voltage expression of literature. Variation of the arc resistivity allows the model to be fitted for different design solutions [10].

The slag bath in a DC smelting furnace typically behaves as an ohmic conductor, unlike the arc which is extremely nonlinear. The electrical resistivity of slag varies widely, from highly conductive slag in ilmenite smelting, to highly resistive slag in applications such as cobalt recovery from non-ferrous slag and nickel laterite smelting.

To model bath's electrical behavior with a fair degree of accuracy, a two-dimensional axisymmetric numerical model is adopted which describes the variation of the potential (voltage) through the bath. The model operates by solving Laplace's equation for potential as described in literature [10]. The equation governs the potential distribution in a material of uniform electrical conductivity, and can be solved numerically using a finite-volume method on a non-uniform mesh [11]. Details of numerical method and geometry adapted can be found in reference literature [10].

Experimental test

Tests were conducted in a pilot 300kW DC arc furnace used for smelting of ferronickel ore fines with the same constructive and geometrical parameters of the furnace which cross section of FEM is presented in figure 2.

Different thermocouples and thermo resistances have been installed at various locations of furnace refractory walls, roof, copper coolers, electrodes, etc to measure average temperature rates in dedicated points (Figure 1). The measurement recording is done with the rapid data logging system "Orion 3530". The recording and evaluation of results has been done in a PC through dedicated software. Figure 3 shows the principal scheme of field data acquisition [6, 12].

The measurement of temperature values in different points of the furnace have been collected in a dedicated hard disc for further evaluation. The average values of measured temperatures at higher total power levels in some points of interest are included in Table1.

To measure experimentally arc resistivity, during the field experiment of furnace, arc characteristic tests have been performed as literature [10] recommend. It is measured the voltage with the power on, and with the electrode at various known heights above the surface of the slag bath to understand the behavior of the voltage drop in the electric arc as a function of its length. The electrode position error was considered negligible. The arc tests performed are carried out for five constant current values (2 kA, 2.8 kA, 4 kA, 6 kA, 10kA) and four different arc lengths (5cm, 10cm, 20cm, 30cm).

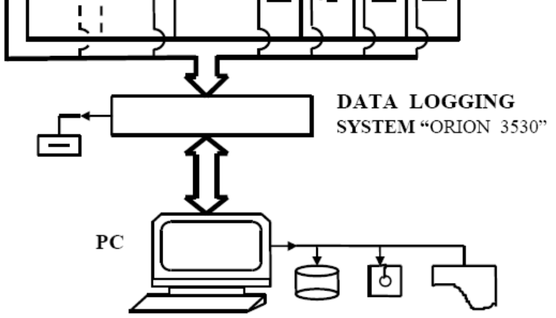

Figure 3. Principal scheme of field data acquisition

To measure experimentally the molten slag resistivities as literature [10] recommend, the electrode of furnace is immersed into the slag layer 10cm and 20cm in depth, with power on. Voltage at these ranges of electrode immersion depths is recorded.

The measurement of current and voltage is done in the supply panel of the furnace with the power monitoring system "Power Sight, PS250, Summit Technologies Inc". The recording and evaluation of results has been done in a PC through dedicated software [13]. The values of voltage, current and power from the beginning of furnace operation until the end of the testing period have measured to understand the variation during furnace start and operation time and compare with values generated from model.

RESULTS

Where a range of temperatures is given in the adopted model, slag bath heat fluxes results of 50kW/m2. Based on steady state temperature field generated by model, the values of heat losses are calculated. The FEM analyses provides estimates of the predicted shell and copper coolers heat losses of 100kW for 50kW/m2 heat flux of slag bath at higher total power levels.

The average test measured values of temperatures at higher power levels are compared with predicted values calculated based on our model in Table 1.

Heat flux values based on the measured temperature data, average operating parameters and general observations during testing indicate that the following conditions prevailed during testing: total current of 1900 A (based on submerged operation at 250 kW average power), a top of metal bath temperature of 1700°C, slag bath heat flux of 35 kW/m2, and, a thick (approximately 80mm) layer of frozen slag, developed during foamy slag operation, covering most of the furnace freeboard and roof hot face.

Table 1. Predicted and measured temperature

Location	Temperatures [°C]	
	Predicted	Measured
Center Hearth	500-700	560
Sidewall at Freeboard	300/1500	220/1100
Sidewall above Hearth	300/1500	250/1300
Sidewall under Hearth	300-400	350
Roof	300/1500	290/1410
Slag Coolers	250	210
Roof shell Plate	100	180
Side shell Plate	100	150
Bottom Shell Plate	100	120

From the measured results the heat flux of slag bath at higher total power levels was 35kW/m2 and total heat losses averaging approximately 80 kW at higher total power levels.

The measured data from experiment of arc characteristic tests are presented graphically in figures 4 and 5.

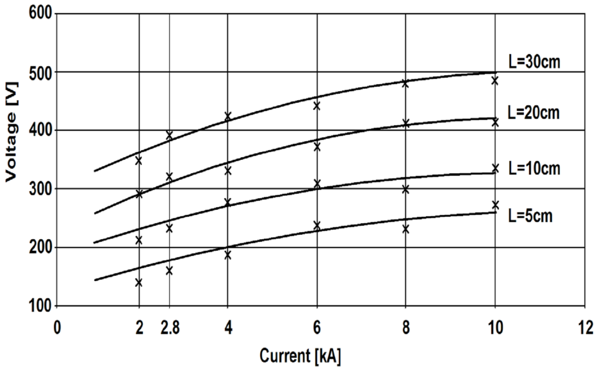

Figure 4. Furnace voltage vs. current for 1.2 Ω cm slag resistivity and 0.018 Ω cm arc resistivity

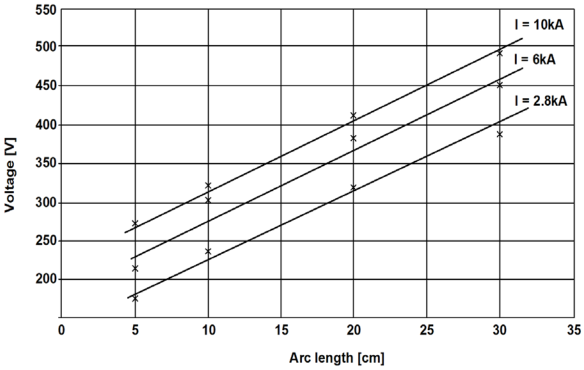

Figure 5. Analysis of arc test data (points) by fitting the arc model (solid line)

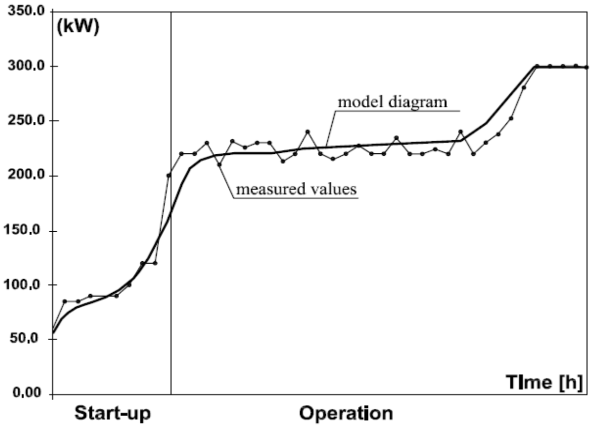

Figure 6. Measured values of electrical power (points) versus values generated from the electrical model (solid line).

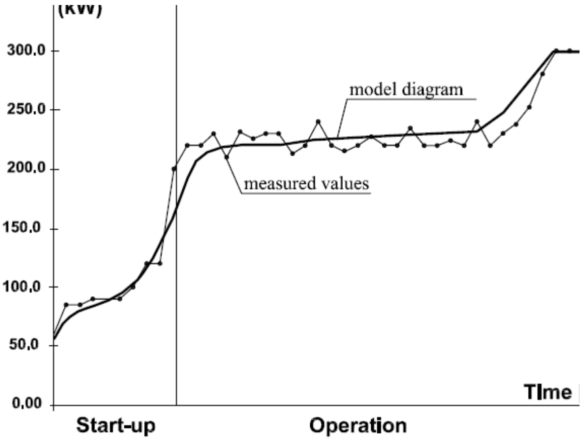

Figure 7. Measured values of current in percentage versus values generated from the electrical model.

In the figure 6 are presented graphically the measured values of power from the beginning of furnace operation until the end of the testing period versus the values generated from the electrical model and in figure 7 the measured values of current.

DISCUSSION

Thermal model

The temperature values generated from model are compared with measured temperatures in order to assess the validity of adopted modeling technique, assumed boundary conditions and linearity's for thermal model of DC furnace. During the process of data comparing is found out that in general, the measured field of temperatures was reasonably close to that predicted as Table 1 show. Some verified discrepancies between measured and predicted temperature field values are attributed to operating conditions of the furnace which differ from the assumed model boundary conditions. For example the layer of frozen slag (which has been neglected in our model) explains the relatively low measured temperatures in the sidewalls (at freeboard), the roof and the tips of the slag level coolers.

Heat flux values, calculated in base of the measured temperature data and heat flux values of the model were found also reasonably near. The finite element analysis of the furnace provided estimates of the predicted shell and copper heat losses of 105 kW for the 50kW/m2 of slag bath heat flux value. For the measured heat flux of 35kW/m2, modeling predictions would suggest losses of approximately 90kW. This estimate agrees reasonably well with total measured heat losses averaging approximately 80 kW at higher total power levels, considering the differences in assumed and actual operating conditions.

Electrical model

In traditional circuit models, the DC arc is often presented as a constant-voltage device, showing no dependence on current at all [10]. In contrast to this our experimental test has shown that DC arc is a more nonlinear type of conductor. Figure 4 shows the relationship between voltage and current for a range of different arc lengths according to experimental arc test data. This fact that is also in accordance with the results of literature [10] is presented in our model. Solid lines in figure 4 are generated from model and this characteristic relationship is stored to be used during designing process.

To understand the behavior of arc plasma resistivity for different arc length with constant current, we measure the values of voltage variation. Since the arc tests performed have been carried out at constant current, the bath voltage can be taken as constant for the duration of a test. Thus the asymptotic slope will be unaffected by whether the value measured is the total voltage or the arc voltage, and the plasma resistivity for a particular process or condition may be calculated directly by the fitting of a straight line to the measured data above a certain arc length. The graph of Figure 5 shows analysis of a set of arc test data (points) by fitting the Bowman arc model (solid line) which is adopted by us.

Knowing by experiment the value of voltage at two different ranges of electrode immersion depths (10cm and 20cm) and the geometry of both the end of the electrode and the slag bath we have calculate the electrical resistivity of the slag of ferronickel as literature [10] recommend. Further experiments are needed to find slag resistivities of other ores.

Knowing arc and slag resistivities for processes, the electrical the adopted model may be used to design the appropriate power supply required from DC arc furnace for smelting of ferronickel ore fines for a known level of voltage or current.

In figure 6 is presented a diagram of electrical power supply of the furnace generated from the model based on known test values of current, arc and slag resistivities. This diagram is compared graphically with the measured values of electrical power.

Otherwise knowing experimentally power diagram, arc and slag resistivities of the furnace, the electrical model may be used to design the values of current for a known stage of operation process. In figure nr.7, the generated diagram of current values is compared graphically with the measured values.

The values generated from the electrical model are shown to be reasonably near to the measured ones in both cases.

It is clear that the electrical model may also specify appropriate ranges of voltage for a known stage of operation process of furnance, knowing the up mentioned values.

CONCLUSIONS

The use of DC arc furnace is considered today an attractive alternative especially in the area of smelting of ores of many varieties.

A thermal 2-D FEM and an electrical model of a DC arc furnace are presented. Experimental test is conducted to improve models and verify assumed boundary conditions, linearities and empirical coefficients in a pilot DC arc furnace used for smelting of ferronickel fine ores. During the experiment, tests of arc characteristics and ferronickel slag resistivities have been performed.

The average steady state field measured values of temperatures at higher total power levels are presented to be compared with predicted values calculated by model. Averaging steady state heat fluxes and heat losses of the test furnace have been calculated and compared with the values generated from the model.

The measured data from experiment of arc characteristic and ferronickel slag tests are presented graphically. The values of arc and ferronickel slag resistivities in processes have been defined experimentally during the test.

Knowing arc and slag resistivities, the electrical model may be used to design the appropriate power supply required from DC arc furnace for smelting of ferronickel ore fines for a known level of voltage or current or vice versa. Values generated from model have been compared graphically with test measurements.

The values generated from the presented thermal and electrical model of the DC arc furnace is shown to be reasonably near to the measured ones. The test furnace validated the adopted modeling concepts, provided valuable experience and yielded information necessary to design a DC arc furnace for smelting of ferronickel ores. We have arrived in these results after a long analyze of all deviations from predicted values and redefining of assumed simplifications, linearitie's and literature recommendations. This technique of improvement based on field experiments and research shall enable further improvements of final result in the future.

In the near future our objective is, that based on the results presented here, to develop dedicated software for designing of DC arc furnaces for smelting of ferronickel ore fines. We are working hard for compiling this software and believe that in a near future shall be able to present it in a paper.

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