A Three Dimensional Simulation Model for a Soderberg Electrode

Magnus Thor Jonsson, Dr.ing.* and Helgi Thor Ingason, Dr.ing.**

*Dept. of Mech. Eng.,University of Iceland, Hjardarhagi 2-6, 107 Reykjavik, Iceland
**Dept. of Quality and Research,Icelandic Alloys Ltd., Grundartangi, Iceland

Abstract

A three dimensional mathematical model of the Söderberg electrode has been developed. The simulation of the electrode can be divided into thermal-electric analysis and stress analysis. The thermal-electric analysis includes the computation of the electro-magnetic field and corresponding currents and heat generation. The model is utilized in two ways. Firstly it is used to calculate the nonuniform outer temperature in the electrode due to central heat in the furnaces. Secondly it is utilized to improve the design of the contact clamps.

Introduction

Söderberg electrodes are widely used in the metallurgical industry, e.g. in the production of ferrosilicon. This paper describes the developement of a three dimensional mathematical model of a Söderberg electrode.

Söderberg electrodes are characterized by the self baking process during production. This means that carbon paste is fed into the upper part of the electrode. It melts as the temperature rises, on the way down. At temperatures in the range of 450-500°C, the paste is baked to form a solid conductor.

Alternating current is fed into the electrode through contact clamps in the baking area, and short-circuited through the bottom. This results in very high temperatures because of the resistivity in the electrode and thermal radiation from the electric arc at the bottom.

Abrupt changes in temperature gradients may lead to high thermal stresses in the electrode. Thiscan lead to electrode breakage with serious consequences for the furnace operation.

Problem description

The bulk of the electrode is made of carbon paste. It is cylindrical and covered with a steel casing, which is neccesary to keep the liquid carbon paste inside the cylinder. Steel fins are placed radially in the cylinder and welded to the casing, binding the baked carbon mass to the casing. Figure 1 shows the geometry of a typical Söderberg electrode. The thermal-electric analysis of the electrode can be divided into two phases which are dependent because of the temperature dependence of the carbon and heat generation from the electric current.

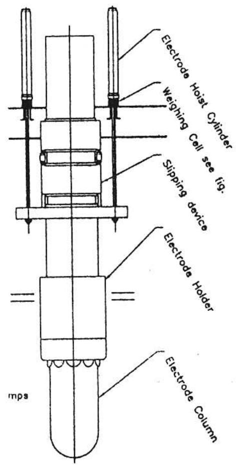

Figure 1: A Söderberg electrode.

- Computation of the electromagnetic field and corresponding currents and heat generation.
- Computation of the time dependent temperature distribution, given the Joule heat generation from the electric currents.

Most of the material constants for the temperature and electric fields e.g. thermal coefficient, density and resistivity are temperature dependent. Electric current through a body, results in thermal energy because of the resistance. This energy is connected to the heat equation. It is then necessary to solve the nonlinear heat equation and the electromagnetic field equations by iteration. This can give convergence problems if the coefficients are highly nonlinear.

In the thermal analysis, a constant temperature is applied on the top of the electrode. The outer surface of the cylinder is under convection load. The bottom surface is under uniform heat flux load.

Modelling was done in ANSYS [6], a finite element package from Swanson Analysis Systems Inc. Computations were performed on a HP workstation at the Mech. Eng. Department at the University of Iceland.

Electromagnetic and thermal analysis

Theory of electromagnetic- and temperature field is presented and discussed. Assumptions and simplifications are pointed out and the boundary conditions are described.

Maxwell's equations

Electromagnetic fields are presented in general by Maxwell's equations. The four equations represent Gauss's law (1), Faraday's law (2) and Amperes law (3)-(4) [15, sec. 21-2].

$$\nabla \cdot \mathbf{D} = \rho_f \tag{1}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{2}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{3}$$

$$\nabla \times \mathbf{H} = \mathbf{J}_f + \frac{\partial \mathbf{D}}{\partial t} \tag{4}$$

The field variables are defined as follows,

D	Electric flux density, C/m^2.
E	Electric field intensity, V/m.
B	Magnetic flux density, $Weber/m^2$.
H	Magnetic field intensity, A/m.
$\mathbf{J}_f$	Free current density, A/m^2.
ρ_f	Free charge density, C/m^3.

The total current density **J** is the sum of the free current density and magnetization current density. If it is assumed that there are no permanent magnets in the matter and no polarization, the following can be defined $\mathbf{D} = \epsilon_0 \mathbf{E}$ and $\mathbf{H} = \frac{1}{\mu}\mathbf{B}$, where μ is the magnetic permeability. Furthermore, there are no free charges in a conductor, so in that case $\rho_f = 0$.

As it is assumed that the fields are ***slowly varying*** at low frequencies, the ***displacement current*** $\frac{\partial \mathbf{D}}{\partial t}$ can be neglected and excluded from (4).

Electromagnetic boundary conditions

General boundary conditions are given for surface discontinuities, which must be applied if material properties change at the boundary. $\mathbf{K}_f$ is defined as the *surface current density* and **n** denoted as the outer normal of the surface. Then boundary conditions at conductor interfaces are given as [15, eq. 21.25-28],

$$\mathbf{n} \cdot (\mathbf{D}_2 - \mathbf{D}_1) = 0$$
$$\mathbf{n} \times (\mathbf{E}_2 - \mathbf{E}_1) = 0$$
$$\mathbf{n} \cdot (\mathbf{B}_2 - \mathbf{B}_1) = 0$$
$$\mathbf{n} \times (\mathbf{H}_2 - \mathbf{H}_1) = \mathbf{K}_f$$

The partial differential equations must be subject to proper boundary conditions to ensure existent and unique solution.

Basically, three special types of boundary conditions are considered. These conditions can be classified as,

- Surface of a good conductor. Conductivity of surroundings much lower than the domain conductivity.
- Current flow into conductor.
- Symmetry condition at appropriate surfaces.

The first case is idealized as a surface of a perfect conductor [15, eq. 26.2]. In the second case, it is assumed that the current density vector is normal to the surface. In the last case symmetry condition is presented. This condition is a natural result of discretization by the Galerkin method. Thus, it is not neccesary to impose symmetry conditions explicity.

The outer electrode area, top of the electrode, outer contact clamps area and lower part of clamps is regarded as perfectly isolated. This means that there is no current and no magnetic flux out of these areas. Voltage potential ϕ is set to zero at the upper part of contact clamps, which is a constraint boundary condition. Current flow is imposed at the bottom, with voltage degrees of freedom coupled to ensure an unique solution.

The temperature field

Temperature distribution in a solid is based on Fourier's law of thermal conduction. The following partial differential equation describes the temperature distribution as a function of time [5, sec. 1.1]. If sufficient boundary conditions are given, the linear problem is well posed.

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + q \tag{5}$$

If the specific heat c, density ρ and thermal conductivity k are temperature dependent, the equation is nonlinear. The source term q is given in watts per unit volume.

There are four types of boundary conditions for a typical thermal conduction problem.

Dirichlet	$T = T_0$
Neumann	$\mathbf{n} \cdot \nabla T = Q_0$
Convection	$\mathbf{n} \cdot \nabla T = h(T - T_w)$
Radiation	$\mathbf{n} \cdot \nabla T = \sigma_0 \epsilon T^4$

Three types of thermal boundary conditions are considered. The temperature at the top of the electrode is set to a constant value. Convection conditions are applied at the whole outer area of the electrode and contact clamps. At the bottom, thermal flux into the bottom is given explicitly.

Given the electric current density J and electric conductivity σ, the Joule heat generation due to resistance in the solid is given by,

$$q = \frac{1}{\sigma} J^2 \tag{6}$$

This is the essential result from the electromagnetic analysis that is used to perform the thermal computations. As the heat generation is approximately a second power function of the applied current the temperature solution is very sensitive to the current load.

Material properties

Two classes of material properties are involved in this analysis of the Söderberg electrode: electromagnetic properties (magnetic permeability, electric conductivity) and thermal properties (thermal conductivity, density, specific heat).

The working conditions for the electrode span very large temperature intervals and the material coefficients are strongly temperature dependent.

The electrode carbon paste is baked at about 500°C and temperatures can be up to 3000°C. Steel melts at about 1350°C so phase changes are assumed to take place at that temperature.

Electromagnetic properties

First the *magnetic permeability* is considered. Permeability of free space is $\mu_0 = 4\pi 10^{-7}$ and the true permeability of a substance is often written as $\mu = \mu_0 \mu_r$ where μ_r is a relative value. A very important aspect, connected to the permeability, is the skin effect, given in (7).

In a time varying magnetic field, currents are induced and are dense at outer surfaces of conductors. This is referred to as the *skin effect*, and the induced currents are called *eddy currents*. It is possible to estimate the thickness of the skin by using the following formula [13, eq. 5.107a],

$$s = \sqrt{\frac{2}{\omega \mu \sigma}} \tag{7}$$

The skin effect acts as an isolator between the two fields on each side of the conductor surface. If the skin depth is very small, thin plates can act like magnetic isolators and therefore partially uncouple the field on each side.

If the relative magnetic permeability of steel is close to one, the skin depth of the steel plates in the electrode is about $67mm$ at least. It can then be assumed that the skin effect is not important in the electrode analysis.

A unit relative permeability of carbon is assumed. High permeabilities are common in iron cores of electric transformers, but the permeability is close to unity for most substances. Electric conductivity is a function of temperature for both steel and baked carbon, and is given in [1, fig. 6].

Thermal properties

Three material coefficients are involved in thermal analysis with a heat source. They are thermal conductivity k, density ρ and specific heat c.

These properties are temperature dependent and will result in a nonlinear analysis. Properties from Elkem Research are used, but are not shown here since they are strictly confidential [12]. Both density and specific heat are of minor interest in the steel casing. The casing and the fins are very small in volume, compared to the carbon paste, the cross sectional area of steel is about one percent of the carbon area. Thermal conductivity of steel is about 30-40 W/m°K for temperatures over 200°C, which is not even an order of magnitude greater than for carbon. It is therefore not important to evaluate thermal conductivity of steel with great accuracy, or dependent of temperature.

Model description

The model has been developed using ANSYS, a general purpose finite element program. The three dimensional model is described with respect to geometry, boundary conditions and volume loads.

Geometry

Three electrodes as shown in figure 1 are placed together in the furnace, forming a 60°angle. Since the temperature in the furnace is largest at the center, we have one symmetry condition that can be utilized to simplify the model to a half-cylinder. Figure 2 shows the placement of electrodes in the furnace.

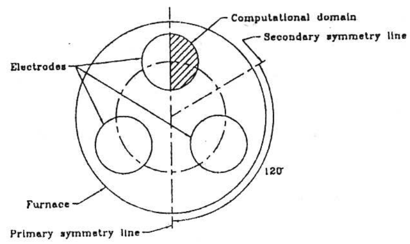

Figure 2: Electrode placement in a furnace.

Various dimensions of the model are given as parameters, making it easy to change the model for different cases. Parameters that can be adjusted are:

- Diameter of the electrode.

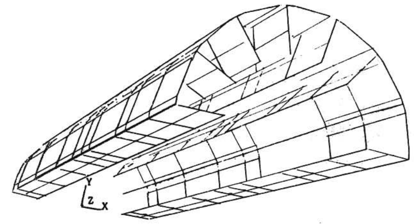

Figure 3: Steel elements in the casing and fins.

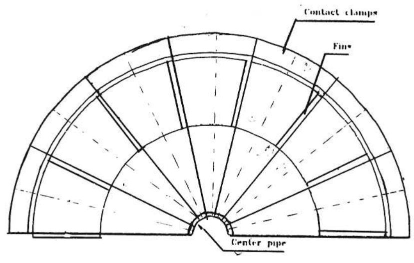

Figure 4: Axial cross section of electrode.

- Casing and fin thickness.
- Number of fins, equally placed in angular position.
- Size of the fins in radial direction into the electrode.
- Diameter of center hole.
- Thickness of steel pipe in center hole.
- Radial position of the center hole, in the symmetry plane.
- Thickness of the contact clamps.
- Total heigth of electrode and contact clamps, plus position of clamps.

The casing is combined of equal size cylindrical sections, welded together. Equally spaced fins are placed on the casing wall, going from the top to some distance below the wall in each casing section.

Figure 5 shows the element model of the electrode with steel fins and contact clamps attached, and figure 4 shows an axial cross section of the electrode with one element division in each part of the electrode.

Element types

First order elements with linear form functions are used in both thermal and electromagnetic computations. These are eight node isoparametric elements.

The electromagnetic element has four degrees of freedom, which consist of the three dimensional vector potential **A** and a time integrated scalar potential ϕ.

The thermal element only has one temperature degree of freedom. This element can be used for nonlinear

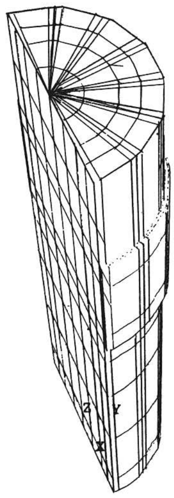

Figure 5: An element mesh of the electrode.

computations, which is necessary because of the temperature dependent material coefficients.

The electrode is formed by appropriate finite elements. It is not feasible to model the thin steel sheets as a complete part of the finite element mesh, since it would result in abrupt changes in the mesh.

We assume that all the fields considered are constant through the thickness of the steel plates. This can be imposed in the finite element formulation by coupling the adjacent corner nodes together in the steel elements. It can be shown, by using the linear properties of the system of equations, that this is equivalent to forcing the field to be constant through the thickness of the thin bricks.

Results

The model has been verified to some extent by composing its results with results from 2-D electrode model by Elkem Carbon. This has yielded positive results. The simulations of both models are comparable for a given case. The model has been utilized for a specific purpose with promising results. An ongoing project has the goal of analyzing the feasibility of an extensive modification of the Söderberg electrode.

For the purpose of this paper the model was used to analyse the size effects of the contact clamps and the consequences of nonuniform temperature distribution at the outer area of the electrode. The results are presented in figures of temperature and heat generation distribution over the symmetry section of the electrode.

The electrode is 1.55 m in diameter, with 2.6 mm thick steel casing and fins. There are 3 metres from bottom to lower part of contact clamps, and the clamps are 1.2 metres high.

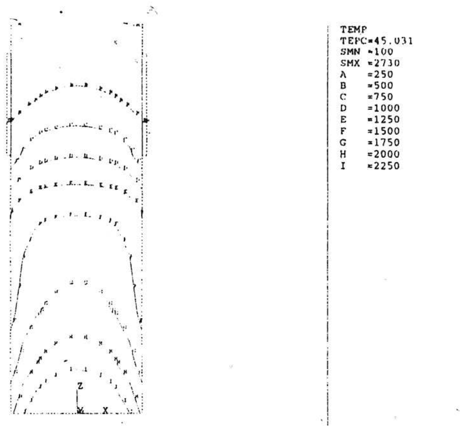

Figure 6: Temperature solution for a uniform outer temperature.

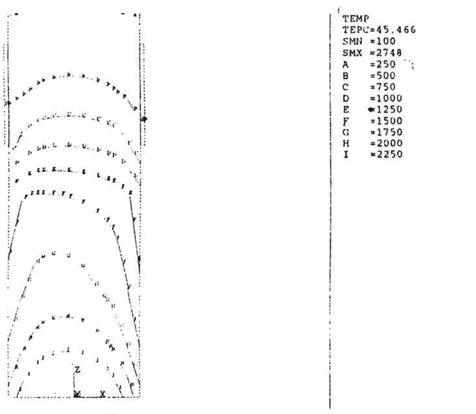

Figure 7: Temperature solution for a nonuniform outer temperature.

An operational condition with 120 kA current load is chosen with a predetermined thermal flux at the bottom, 16000 W. The convection parameters are considered nonuniform over the whole electrode, and adjusted to obtain acceptable results.

Nonuniform outer temperature

The outer temperature of the electrode is not uniform, because of the heat generation in the center of the electrode as shown in figure 2.

In the equation $q = hA(T - T_\infty)$, h is set to 22 and T_∞ is between 300°to 700°C. The top of the electrode is kept at a constant temperature of 100°C and the temperature outside the contact clamps is 200°C .

Figure 6 shows the thermal conditions after convergence of the coupled thermal-electromagnetic computations for the uniform case. The baking area at 500°C is at the lower tip of the contact clamps [7]. Figure 7 shows the effect of nonuniform outer temperature.

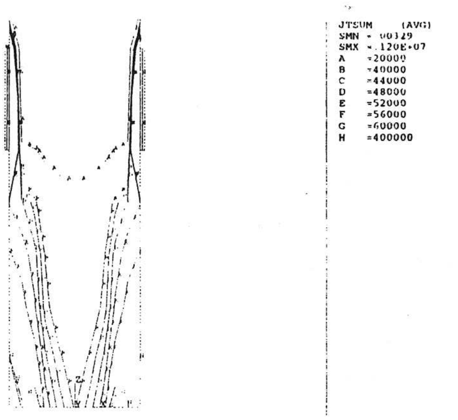

Figure 8: Current density for real contact clamps.

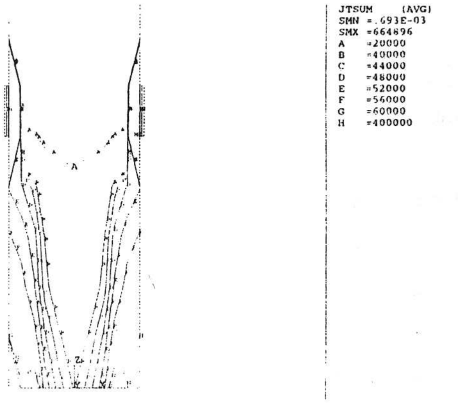

Figure 9: Current density for contact clamps with half size.

Contact clamps

A steady state analysis with different size of the contact clamps is considered. Figure 9 shows the current density where the sizes of the contact clamps are half of the real size. Compared to the figure 8 the difference in the current density is negligible. For smaller clamps the heat generated is more uniform with a less temperature gradient.

Conclusions and Discussion

The two problems presented in this paper were chosen to show how the model can be utilized to answer questions that conventional 2-D models can't. It is well known that the temperature in a submerged arc furnace is in maximum in the center, between the electrodes, but decreases towards the site walls. The simulations confirm that the temperature gradient in the furnace will lead to non-uniform temperature distribution in the electrode. The simulation with to different sizes of contact clamps indicate that the current distribution would not be disturbed by decreasing the contact clamps by half. Knowing that the conventional contact clamps are made of copper, it seems that some saving in the investment and maintenance of the Söderberg electrode could be reached.

Further development of the model is in progress and ongoing activities include a detailed verification. This is done by making temperature measurements on a full scale Söderberg electrode at Grundartangi, Iceland.

Another ongoing activity is a sensitivity analysis on the ANSYS model where the sensitivity of the model results to changes in the boundary conditions and the material properties of the electrode paste are mapped. This will help to focus on the most important material- and model properties. A continuation of this work is to re-measure the corresponding material properties, thus making a more solid base for the model simulations.

Another important field are the boundary conditions of the model. These are somewhat simplified, e.g. at the electrode tip where improvements are required and better understanding of how the arc influences the temperature distribution and the thermal stresses is needed. In addition, IA experience shows that the electrode is far from being a regular cylinder in shape near the electrode tip. These irregularities in the shape might influence the conditions higher up in the electrode.

Acknowledgments

The authors wish to thank Icelandic Allyos and ELKEM Carbon of Norway for supporting this work. This work has also been supported bye the Research Council of Iceland, The Research Fund of the University of Iceland, hereby gratefully acknowledged.

References

[1] Arne Georg Arnesen, Sigmund Oekstad, Reidar Innvaer, and Leif Olsen. Operation of soederberg electrodes, 1978. Ilafa-Congres, Acapulco.

[2] K. J. Binns, P. J. Lawrenson, and C. W. Trowbridge. *The Analytical and Numerical Solution of Electric and Magnetic fields.* John Wiley & Sons Ltd, 1992.

[3] Robert D. Cook, David S. Malkus, and Michael E. Plesha. *Concepts and Applications of Finite Element Analysis.* John Wiley & Sons Ltd, third edition, 1989.

[4] Christophe Guérin et. al. A shell element for computing 3d eddy currents – application to transformers. *IEEE Transactions on Magnetics,* 31(3):1360–1363, 1995.

[5] J. P. Holman. *Heat Transfer.* McGraw-Hill book company, seventh edition, 1992.

[6] Swansons Analysis Systems Inc. Ansys user manual.

[7] Helgi Thor Ingason. *Hollow Electrodes in the Production Process for Ferrosilicon.* PhD thesis, Technical University of Norway, September 1994. Institute of Metallurgy.

[8] Reidar Innvaer. A status for the soederberg smelting electrode. ELKEM intern report, August 1992.

[9] Reidar Innvaer, Knut Fidje, and Terje Sira. Three-dimensional calculations on smelting electrodes. *Modeling, identification and control,* 8(2):103–115, 1997.

[10] Reidar Innvaer, Knut Fidje, and Reidar Ugland. Effect of current variations on material properties and thermal stresses in soederberg electrodes. INFACON 86, Rio De Janeiro.

[11] Reidar Innvaer, Leif Olesen, and Arnfinn Vatland. Operational parameters for soederberg electrodes from calculations, measurements and plant experience, 1984. Mintek 50, Johannesburg.

[12] Elkem Research. Material properties. Confidential intern paper.

[13] L. Solymar. *Lectures on Electromagnetic Theory.* Oxford University Press, Ely House, London W.1, 1976.

[14] Charles W. Steele. *Numerical Computation of Electric and Magnetic Fields.* Van Nostrand Reinhold Company Inc., 115 Fifth Avenue, New York, 1987.

[15] Roald K. Wangsness. *Electromagnetic Fields.* John Wiley & Sons Ltd, second edition, 1986.