FEM CALCULATIONS CURRENT FLOW FOR SUBMERGED ARC FURNACES AND EDDY CURRENTS/HEAT TRANSFER FOR POWER CABLES

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CONTENTS

1 INTRODUCTION[1]:

1.1 OVERVIEW:

Along this proyect, FEMM program will be used. FEMM is a suite of programs for solving low frequency electromagnetic problems on 2-Dimensional planar and axisymmetric domains. The program currently addresses linear/nonlinear *magntostatic problems*, *linear/nonlinear time harmonic magnetic problems, linear electrostatic problems, and steady-state heat flow problems.*

1.2 KINDS OF PROBLEMS AVAILABLE IN FEMM

FEMM addresses some limiting cases of Maxwell's equations. The magnetics problems addressed are those that can be consided as "low frequency problems," in which displacment currents can be ignored. Displacement currents are typically relevant to magnetics problems only at radio frequencies. In a similar vein, the electrostatics solver considers the converse case in which only the electric field is considered and the magnetic field is neglected. FEMM also solves 2D/axysymmetric steady-state heat conduction problems. This heat conduction problem is mathematically very similar to the solution of electrostatic problems.

1.2.1 MAGNETIC PROBLEMS

1.2.1.1 Relevant Partial Differential Equations

In this proyect only approach Magnetostatic Problems. Magnetostatic problems are problems in which the fields are time-invariant. In this case, the field intensity (H) and flux density (B) must obey:

$$\nabla \times H = J \tag{1.1}$$

$$\nabla \cdot B = 0 \tag{1.2}$$

subject to a constitutive relationship between B and H for each material:

$$B = \mu H \tag{1.3}$$

If a material is nonlinear (e.g. saturating iron or alnico magnets), the permeability, is actually a function of B:

$$\mu = B / H(B) \tag{1.4}$$

FEMM goes about finding a field that satisfies (1.1)-(1.3) via a magnetic vector potential approach.

Flux density is written in terms of the vector potential, A, as:

$$B = \nabla \times A \tag{1.5}$$

Now, this definition of B always satisfies (1.2). Then, (1.1) can be rewritten as:

$$\nabla \times [1/\mu(B)]\, \nabla \times A = J \tag{1.6}$$

For a linear isotropic material (and assuming the Coulomb gauge, $\nabla \cdot A = 0$), eq. (1.6) reduces to:

$$-1/\mu\, \nabla^2 A = J \tag{1.7}$$

FEMM retains the form of (1.6), so that magnetostatic problems with a nonlinear B-H relationship can be solved.

In the general 3-D case, A is a vector with three components. However, in the 2-D planar and axisymmetric cases, two of these three components are zero, leaving just the component in the "out of the page" direction. The advantage of using the vector potential formulation is that all the conditions to be satisfied have been combined into a single equation. If A is found, B and H can then be deduced by differentiating A. The form of (1.6), an elliptic partial differential equation, arises in the study of many different types of engineering phenomenon. There are a large number of tools that have been developed over the years to solve this particular problem.

1.2.1.2 Boundary Conditions

Some discussion of boundary conditions is necessary so that the user will be sure to define an adequate number of boundary conditions to guarantee a unique solution.

Boundary conditions for magnetic and electrostatic problems come in five varieties:

· ***Dirichlet***. In this type of boundary condition, the value of potential A or V is explicitly defined on the boundary, e.g. A = 0. The most common use of Dirichlet-type boundary conditions in magnetic problems is to define A = 0 along a boundary to keep magnetic flux from crossing the boundary. In electrostatic problems, Dirichlet conditions are used to fix the voltage of a surface in the problem domain.

· ***Neumann.*** This boundary condition specifies the normal derivative of potential along the boundary. In magnetic problems, the homogeneous Neumann boundary condition, $\partial A/\partial n = 0$ is defined along a boundary to force flux to pass the boundary at exactly a 90o angle to the boundary. This sort of boundary condition is consistent with an interface with a very highly permeable metal.

· ***Robin.*** The Robin boundary condition is sort of a mix between Dirichlet and Neumann, prescribing a relationship between the value of A and its normal derivative at the boundary.

An example of this boundary condition is:

$$\partial A/\partial n + cA = 0$$

This boundary condition is most often in FEMMto define "impedance boundary conditions" that allow a bounded domain to mimic the behaviour of an unbounded region. In the context of heat flow problems, this boundary condition can be interpreted as a convection boundary condition. In heat flow problems, radiation boundary conditions are linearized about the solution from the last iteration. The linearized form of the radiation boundary condition is also a Robin boundary condition.

· ***Periodic A.*** Periodic boundary conditions joins two boundaries together. In this type of boundary condition, the boundary values on corresponding points of the two boundaries are set equal to one another.

· ***Antiperiodic.*** The antiperiodic boundary condition also joins together two boundaries. However, the boundary values are made to be of equal magnitude but opposite sign.

If no boundary conditions are explicitly defined, each boundary defaults to a homogeneous Neumann boundary condition. However, a non-derivative boundary condition must be defined somewhere (or the potential must be defined at one reference point in the domain) so that the problem has a unique solution.

For axisymmetric magnetic problems, $A = 0$ is enforced on the line $r = 0$. In this case, a valid solution can be obtained without explicitly defining any boundary conditions, as long as part of the boundary of the problem lies along $r = 0$. This is not the case for electrostatic problems, however.

For electrostatic problems, it is valid to have a solution with a non-zero potential along $r = 0$.

1.2.1.3 Pre-processor

The preprocessor is used for *drawing the problems geometry*, *defining materials*, and *defining boundary conditions*. A new instance of the pre-processor can be created by selecting File | Newoff of the main menu and then selecting "Magnetics Problem" from the list of problem types which then appears.

Drawing a valid geometry usually consists of four (though not necessarily sequential) tasks:

· Drawing the endpoints of the lines and arc segments that make up a drawing.

· Connecting the endpoints with either line segments or arc segments

· Adding "Block Label" markers into each section of the model to define material properties and mesh sizing for each section.

· Specifying boundary conditions on the outer edges of the geometry.

The *definition of problem* type is specified by choosing the Problem selection off of the main menu. Selecting this option brings up the Problem Definition dialog, shown in Figure 1

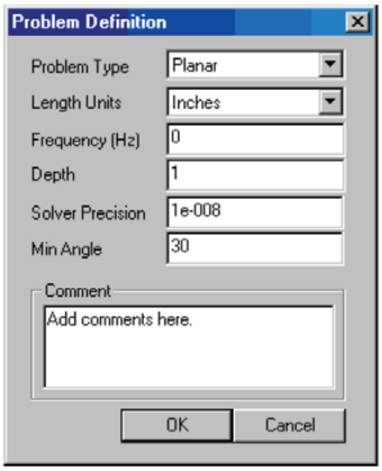


Figure 1: Problem Definition dialog

To make a solvable problem definition, the user must identify boundary conditions, block materials properties, and so on. The different types of properties defined for a given problem are defined via the Properties selection off of the main menu.

When the Properties selection is chosen, a drop menu appears that has selections for Materials, Boundary, Point, and Circuits. When any one of these selections is chosen, the dialog pictured in Figure 2 appears.

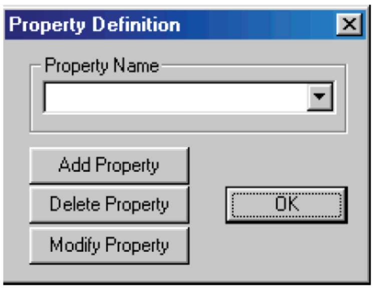


Figure 2: Property Definition dialog box

This dialog is the manager for a particular type of properties. All currently defined properties are displayed in the Property Name drop list at the top of the dialog.

At the beginning of a new model definition, the box will be blank, since no properties have yet been defined.

The Boundary Property dialog box is used to specify the properties of line segments or arc segments that are to be boundaries of the solution domain. When a new boundary property is added or an existing property modified, the Boundary Property dialog pictured in Figure 3 appears.

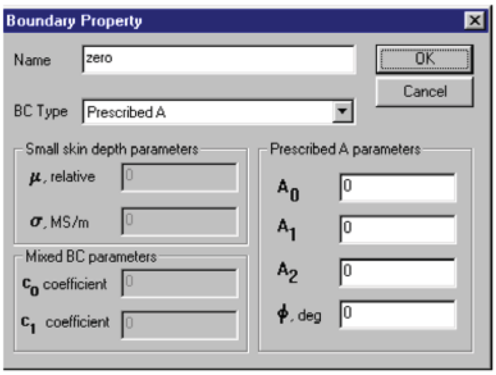


Figure 3: Boundary Property dialog.

The first selection in the dialog is the Name of the property. The default name is "New Boundary," but you should change this name to something more descriptive of the boundary that is being defined.

The next selection is the BC Type drop list. This specifies the boundary condition type. Currently, FEMM supports the following types of boundaries:

· *Prescribed A* If the problem is planar, the parameters correspond to the formula:

$$A = (A_0+A_1x+A_2y)e^{j\varphi} \quad (2.2)$$

If the problem type is axisymmetric, the parameters correspond to:

$$A = (A_0+A_1r+A_2z)e^{j\varphi} \quad (2.3)$$

· *Small Skin Depth.* The result is a Robin boundary condition with complex coefficients of the form:

$$(\partial A/\partial n) + (1+j)/\delta \; A = 0 \quad (2.4)$$

· *Mixed* This denotes a boundary condition of the form:

$$(1 / \mu_r\mu_o)(\partial A/\partial n) + c_o A + c_1 = 0$$

The Block Property dialog box is used to specify the properties to be associated with block labels. The properties specified in this dialog have to do with the material that the block is composed of, as well as some attributes about how the material is put together (laminated). When a new material property is added or an existing property modified, the Block Property dialog pictured in Figure 4 appears.

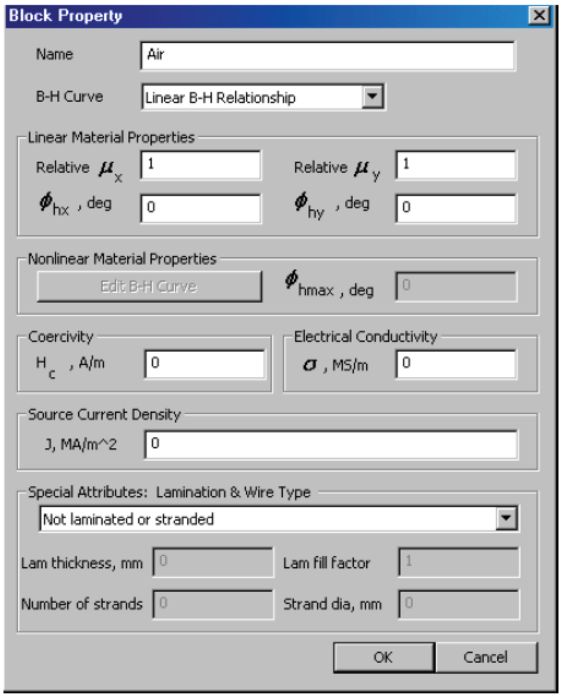


Figure 4: Block Property dialog

1.2.1.4 Postprocessor

The the magnetics postprocessing functionality of femm is used to view solutions generated by the fkern solver. A magnetics postprocessor window can be opened either by loading some previously run analyses via File|Open on themainmenu, or by pressing the "bigmagnifying glass" icon from within a preprocessor window to view a newly generated solution. Magnetics postprocessor data files stored on disk have the .ans prefix.

Similar to the preprocessor, the postprocessor always operates in one of three modes, depending upon the task to be performed. These modes are:

· *Point Values Mode*. In this mode, the user can click on various points in the solution region. Local field values are then listed in the FEMM Output window.

· *Contour Mode.* This mode allows the user to define arbitrary contours in the solution region. Once a contour is defined, plots of field quantities can be produced along the contour, and various line integrals can be evaluated along the contour.

Currently, the type of line plots supported is:

- Vector potential along the contour;
- Magnitude of the flux density along the contour;
- Component of flux density normal to the contour;
- Component of flux density tangential to the contour;
- Magnitude of the field intensity along the contour;

· Component of field intensity normal to the contour;

· Component of field intensity tangential to the contour;

· *Block Mode*. The Block Mode lets the user define a subdomain in the solution region. Once the block has been defined, a variety of area and volume integrals can be taken over the defined sub domain. Integrals include stored energy (inductance), various kinds of losses, total current in the block, and so on. The block integrals currently supported are:

· Average temperature over volume

· Block cross-section area

· Block volume

· Average F over volume

· Average G over volume

1.2.2 HEAT FLOW PROBLEMS

1.2.2.1 Relevant Partial Differential Equations.

The heat flow problems address by FEMM is essentially steady-state heat conduction problems. These problems are represented by a temperature gradient, G(analogous to the field intensity, E for electrostatic problems), and heat flux density, F(analogous to electric flux density, D, for electrostatic problems).

The heat flux density must obey Gauss' Law, which says that the heat flux out of any closed volume is equal to the heat generation within the volume. Analogous to the electrostatic problem, this law is represented in differential form as:

$$\nabla \cdot F = q \qquad (1.21)$$

where q represents volume heat generation.

Temperature gradient and heat flux density are also related to one another via the constitutive relationship:

$$F = kG \qquad (1.22)$$

where k is the thermal conductivity. Thermal conductivity is often a weak function of temperature.

FEMM allows for the variation of conductivity as an arbitrary function of temperature.

Ultimately, one is generally interested in discerning the temperature, T, rather than the heat flux density or temperature gradient. Temperature is related to the temperature gradient, G, by:

$$G = -\nabla T \qquad (1.23)$$

Substituting (1.23) into Gauss' Law and applying the constitutive relationship yields the second order partial differential equation:

$$-\nabla \cdot (k \nabla T) = q \quad (1.24)$$

FEMM solves (1.24) for temperature T over a user-defined domain with user-defined heat sources and boundary conditions.

1.2.2.2 Boundary Conditions

There are six types of boundary conditions for heat flow problems:

· ***Fixed Temperature.*** The temperature along the boundary is set to a prescribed value.

· ***Heat Flux.*** The heat flux, f , across a boundary is prescribed. This boundary condition can be represented mathematically as:

$$k\,(\partial T/\partial n) + f = 0 \quad (1.37)$$

where n represents the direction normal to the boundary.

· ***Convection.*** Convection occurs if the boundary is cooled by a fluid flow. This boundary condition can be represented as:

$$k(\partial T/\partial n + h(T - T_o) = 0 \quad (1.38)$$

where h is the "heat transfer coefficient" and To is the ambient cooling fluid temperature.

· ***Radiation.*** Heat flux via radiation can be described mathematically as:

$$k(\partial T/\partial n) + \beta k_{sb}(T^4 - T_o^4) = 0 \quad (1.39)$$

where beta is the emissivity of the surface (a dimensionless value between 0 and 1) and k_{sb} is the Stefan-Boltzmann constant.

· ***Periodic***. A periodic boundary conditions joins two boundaries together. In this type of boundary condition, the boundary values on corresponding points of the two boundaries are set equal to one another.

· ***Antiperiodic***. The antiperiodic boundary condition also joins together two boundaries. However, the boundary values are made to be of equal magnitude but opposite sign.

If no boundary conditions are explicitly defined, each boundary defaults an insulated condition (i.e. no heat flux across the boundary). However, a non-derivative boundary condition must be defined somewhere (or the potential must be defined at one reference point in the domain) so that the problem has a unique solution.

1.2.2.3 Pre-processor

The pre-processor is used for drawing the problems geometry, defining materials, and defining boundary conditions. The process of construction of heat flow problems is mechanically nearly identical to the construction of magnetic problems–refer to Sections 1.2.1.3.

The Boundary Property dialog box is used to specify the properties of line segments or arc

segments that are to be boundaries of the solution domain. When a new boundary property is added or an existing property modified, the Boundary Property dialog pictured in Figure 5 appears.

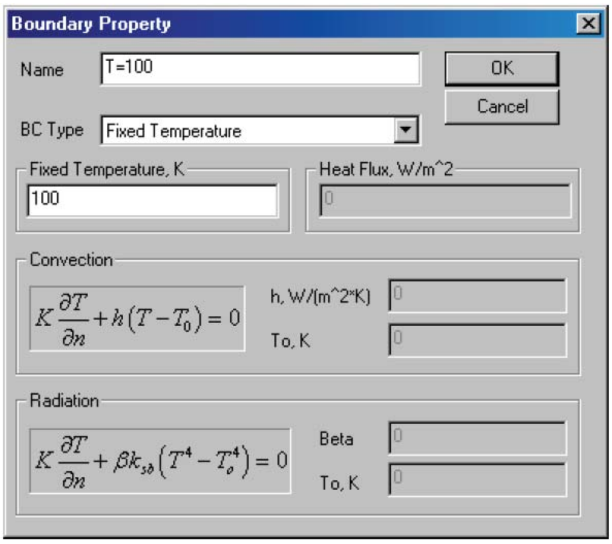


Figure 5: Boundary Property dialog

The first selection in the dialog is the Name of the property. The default name is New Boundary, but you should change this name to something more descriptive of the boundary that is being defined.

The next selection is the BC Type drop list. This specifies the boundary condition type. Currently, FEMM heat flow problems support the following types of boundaries: Fixed Temperature, Heat Flux, Convection, Radiation, Periodic, and Antiperiodic. Boundary conditions are described in detail in Section 1.2.2.2.

1.2.2.4 Postprocessor

Operation of the heat flow postprocessor (i.e. modes, view manipulation) is very similar to that of the magnetic postprocessor. Refer to Sections 1.2.1.4.

the postprocessor always operates in one of three modes, depending upon the task to be performed. These modes are:

·*Point Values Mode.*

·*Lines Values Mode*. The line integrals currently supported are:

· Temperature Difference (G.t). This integral returns the temperature difference between the ends of the contour

· Heat Flux (F.n). This integral returns the total heat flux passing through a volume defined by extruding or sweeping the defined contour.

· Contour length & area. The length of the contour and the area formed by extruding the contour.

· Average temperature. The average temperature along the line.

·*Block Values Mode*. The block integrals currently supported are:

· Average temperature over volume

· Block cross-section area

· Block volume

· Average F over volume

· Average G over volume

1.2.3 CURRENT FLOW PROBLEMS

1.2.3.1 Relevant Partial Differential Equations.

The current flow problems solved by FEMM are essentially quasi-electrostatic problems in which the magnetic field terms in Maxwell's equations can be neglected but in which the displacement current terms (neglected in magnetostatic and eddy current problems) are relevant.

Again restating Maxwell's Equations, the electric and magnetic fields must obey:

$$\nabla \times H = J + \dot{D} \tag{1.25}$$

$$\nabla \cdot B = 0 \tag{1.26}$$

$$\nabla \times E = -\dot{B} \tag{1.27}$$

$$\nabla \cdot D = \rho \tag{1.28}$$

subject to the constitutive relations:

$$J = \sigma E \tag{1.29}$$

$$D = \varepsilon E \tag{1.30}$$

The divergence of (1.25) can be taken to yield:

$$\nabla \cdot (\nabla \times H) = \nabla \cdot J + \nabla \cdot \dot{D} \tag{1.31}$$

By application of a standard vector identity, the left-hand side of (1.31) is zero, leading to:

$$\nabla \cdot J + \nabla \cdot \dot{D} = 0 \tag{1.32}$$

As before, we can assume an electric potential, V, that is related to field intensity, E, by:

$$E = -\nabla V \tag{1.33}$$

Because the flux density, B, is assumed to be negligibly small, (1.26) and (1.27) are suitably satisfied by this choice of potential.

If a phasor transformation is again assumed, wherein differentiation with respect to time is replaced by multiplication by jω, the definition of voltage can be substituted into (1.32) to yield:

$$-\nabla\cdot\ ((\sigma+ j\omega\varepsilon)\nabla V) = 0 \qquad (1.34)$$

If it is assumed that the material properties are piece-wise continuous, things can be simplified slightly to:

$$-(\sigma+ j\omega\varepsilon)\ \ \nabla^2 V = 0 \qquad (1.35)$$

FEMM solves (1.35) to analyze current flow problems.

Eq. (1.35) also applies for the solution of DC current flow problems. At zero frequency, theterm associated with electrical permittivity vanishes, leaving:

$$-\sigma\nabla 2V = 0 \qquad (1.36)$$

By simply specifing a zero frequency, this formulation solves DC current flow problems in a consistent fashion.

1.2.3.2 Boundary Conditions

There are five types of boundary conditions for heat flow problems:

· ***Fixed Voltage.*** The voltage along the boundary is set to a prescribed value.

· ***Periodic***. A periodic boundary conditions joins two boundaries together. In this type of boundary condition, the boundary values on corresponding points of the two boundaries are set equal to one another.

· ***Antiperiodic***. The antiperiodic boundary condition also joins together two boundaries. However, the boundary values are made to be of equal magnitude but opposite sign.

· ***Mixed***

· ***Surface Current Density***

1.2.3.3 Pre-processor

The preprocessor is used for *drawing the problems geometry*, *defining materials*, and *defining boundary conditions*. The process of construction of current flow problems is mechanically nearly identical to the construction of magnetic problems–refer to Sections 1.2.1.3 or Heat Flow Problems in 1.2.2.3. This section considers those parts of problem definition that are unique to current flow problems.

To make a solvable problem definition, the user must identify boundary conditions, block materials properties, and so on. The different types of properties defined for a given problem are defined via the Properties selection off of the main menu.

When the Properties selection is chosen, a drop menu appears that has selections for Materials, Boundary, Point, and Conductors. When any one of these selections is chosen, the dialog pictured in Figure 6 appears.

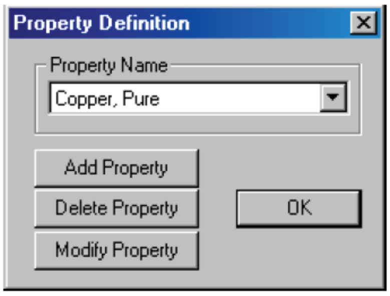


Figure 6: Property Definition dialog box.

This dialog is the manager for a particular type of properties. All currently defined properties are displayed in the Property Name drop list at the top of the dialog. At the beginning of a new model definition, the box will be blank, since no properties have yet been defined. Pushing the Add Property button allows the user to define a new property type. The Delete Property button removes the definition of the property currently in view in the Property Name box. The Modify Property button allows the user to view and edit the property currently selected in the Property Name box. Specifics for defining the various property types are addressed in the following subsections. See figure 7.

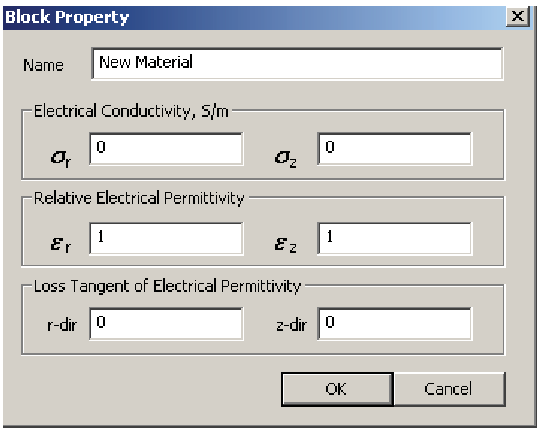


Figure 7: Property Material Definition dialog box

The Boundary Property dialog box is used to specify the properties of line segments or arc segments that are to be boundaries of the solution domain. When a new boundary property is added or an existing property modified, the Boundary Property dialog pictured in Figure 2.54 appears.

The first selection in the dialog is the Name of the property. The default name is New Boundary, but you should change this name to something more descriptive of the boundary that is being defined.

The next selection is the BC Type drop list. This specifies the boundary condition type. Currently, FEMM supports the following types of boundaries: Fixed Voltage, Mixed, Prescribed surface current density, Periodic, and Antiperiodic.

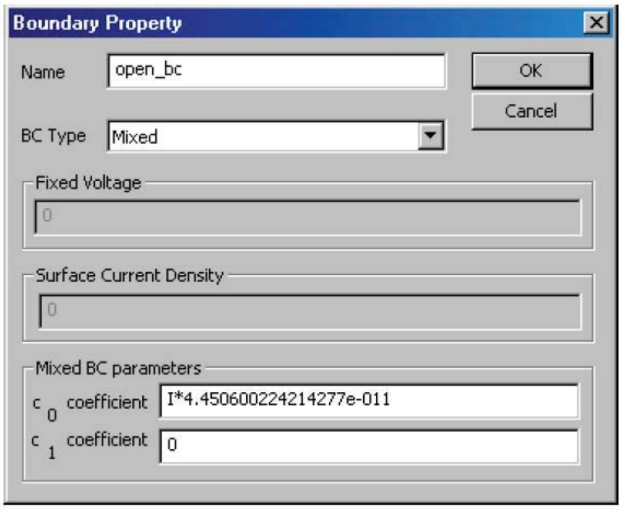


Figure 8: Boundary Property dialog.

The purpose of the conductor properties is mainly to allow the user to apply constraints on the total amount of current flowing in and out of a surface. Alternatively, conductors with a fixed voltage can be defined, and the program will compute the total current flow through the during the solution process.

For fixed voltages, one could alternatively apply a Fixed Voltage boundary condition. However, applying a fixed voltage as a conductor allows the user to group together several physically disjoint surfaces into one conductor upon which the total current flow is automatically computed. The dialog for entering conductor properties is pictured in Figure 9.

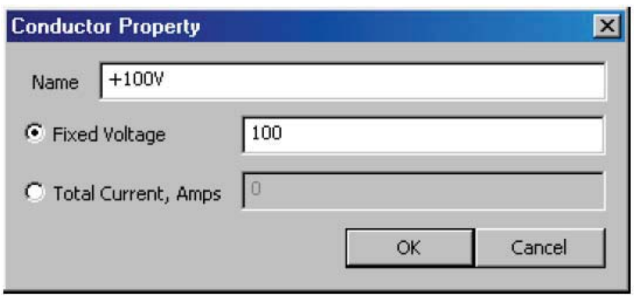


Figure 9: Conductor Property dialog.

1.2.3.4 Postprocessor

Operation of the current flow postprocessor (i.e. modes, view manipulation) is very similar to that of the magnetic postprocessor. Refer to Sections 1.2.1.4.

The postprocessor always operates in one of this modes, depending upon the task to be performed. These modes are:

·*Lines plots.* Currently, the type of line plots supported are:

- V Voltage
- |J| Magnitude of current density
- J.n Normal current density
- J.t Tangential current density
- |E| Magnitude of electric field intensity
- E.n Normal electric field intensity
- E.t Tangential electric field intensity
- |Jc| Magnitude of conduction current density
- Jc.n Normal conduction current density
- Jc.t Tangential conduction current density
- |Jd| Magnitude of displacment current density
- Jd.n Normal displacement current density
- Jd.t Tangential displacement current density

·*Lines Integrals.*

· E.t This integral returns the voltage drop along the defined contour

· D.n. This integral returns the total electric flux passing through a volume defined by extruding or sweeping the defined contour. If this integral is performed over a closed contour, the resulting quantity is equal to the charge contained inside the contour.

· Contour Length/Area. This integral returns the length of the defined contour in meters, as well as the area of the extruded or swept volume associated with the defined contour.

· Force from stress tensor. This integral totals the force produced on the contour derived from Maxwell's stress tensor. Deriving meaningful force results requires some care inthe choice of integration path; refer to Section 2.5.7 for a detailed discussion of force and torque calculation.

· Torque from stress tensor. This selection integrates the torque about the point (0,0) inferred from Maxwell's stress tensor. Again, some guidelines must be followed to getaccurate torque results.

· *Block Values Mode*. The block integrals currently supported are:

· Stored Energy This selection calculates the energy stored in the electric field in the specified

region by integrating (12 D· E) over the selected area.

· Block cross-section area.

· Block volume.

· Average D over volume.

· Average E over volume.

· Force via Weighted Stress Tensor. The Weighted Stress Tensor block integrals automatically compute a weighting function over the finite element mesh that allows all possible air elements to contribute to the stress tensor integration. This approach is similar to the weighted stress tensor approach described in [7] and/or [8]. To compute the force on a region or set of regions, the user selects the blocks upon which force result is desired and selects the Force via Weighted Stress Tensor integral.

· Torque via Weighted Stress Tensor. This integral is torque version of the Force via Weighted Stress Tensor integral. Instead of force, torque about (0,0) is computed using the same weighting function approach.

2 PROJECT OBJECTIVES

2.1 FURNACES [2]

In this first objective, all is refer to furnaces in the FeNi technology. The FeNi technology is currently dominated by high-power submerged arc furnaces, often designed as smelter as "two-in-line-solution". To achieve the intended high efficiency, state-of-the-art design in good correlation with ores and reductants and an integrated layout of the whole plant is of great importance.

During the last century, the submerged arc furnace has been one of metallurgy's most amazing diversified melting units which have found many applications in over 20 different industrial areas, including ferro-alloys, iron, silicon metal, copper, lead. Zinc, refractory, titanium oxide, calcium carbide, phosphorus and materials recycling, etc.

The strong competitiveness of submerged arc furnaces for ferroalloys has been mainly achieved by the installation of advanced high-power smelting units. During the last decade numerous improvements had been developed proving efficient and safe operation with large scale FeNi-furnaces. This new demand led to the development of various sidewall cooling concepts as well as to the development of AC thyristor controls, which allow better operational control, higher and more efficient power input and results in less mechanical stress of the furnace equipment. Another trend is to design the smelters to a maximum possible capacity. Regarding the high energy efficiency, these may be round or rectangular-shaped furnaces, depending on the requested capacity.

In principle, the smelter unit in the FeNi plant comprises:

- The calcine transport system,
- The slag and metal tapping facilities,
- The off gas system
- The refining plant and
- The metal granulation plant.

The principle of a submerged arc furnace is resistance heating. Electric energy is converted into heat and reduction energy by using the resistance R of the burden or the molten slag, sometimes, e.g. in the case of FeNi production, reinforced by the electrical resistance of an arc between the slag and electrode.

The electric energy is transferred into the furnace via 6 in-line self-baking electrodes arranged at the centreline of the furnace. The electrode arrangements depend on the process and the installed power. The electric power is normally supplied from the furnace transformers via high current lines, water-cooled flexible, bus tubes at the electrodes and the contact clamps into the electrodes. Today, control and supervision are affected by a PLC and visualisation system.

The electrode is consumed by oxidation in the slag bath and the furnace freeboard. The self-baking electrodes with casings are periodically extended by new pieces. The electrode is semi-automatically slipped into the bath with the furnace at full electric load and with no interruptions in furnace operation. The electrode column assemblies contain all facilities to hold, slip and regulate the penetration into the bath. All operations on the electrodes are performed hydraulically. [The dimensioning of those movements is the case of study in this project].

Metal and slag are tapped periodically by means of drilling machine and closed either by a manually placed lug or a mud gun. Metal is tapped into ladles, slag/matte is either tapped into slag pots, dry pits or granulation systems.

Successful operation is always based on the right choice of furnace design and furnace dimensions. Prior to each project, a expert team generally follows the design steps shown below:

1º Choice of raw materials and desired production rate per hour in intensive dialogue with customer. The choice of the raw material according to the customer's aspects has the biggest impact on the process. On the one hand it affects the slag composition and on the other hand the smelting pattern inside the furnace. We can choose between this types of energy input according to the process and the physical properties of the raw material:

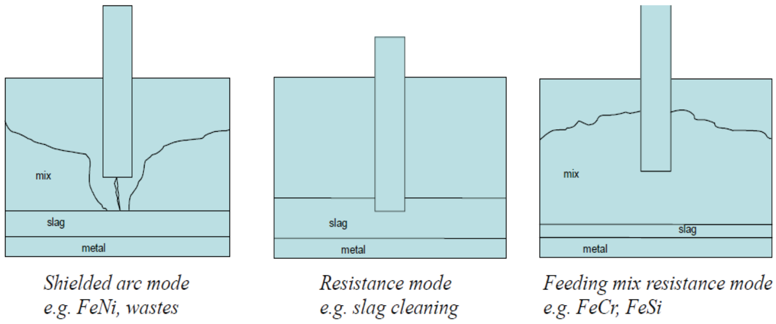


Figure 10. Kinds of furnaces depends on types energy inputs

In this project all the calculations will be about the second type, resistance mode.

2º Metallurgical Calculations.

3º Choice of the applied technology and kind of energy input.

4º Assumption of thermal losses.

5º Dimensioning of mechanical data.

6º Recalculation of thermal losses.

7º Calculation of electrical losses.

8º Dimensioning of electrical equipment.

9º Definition of nominal load.

10º Definition of guaranties.

Of course, the describe steps will change if the customer mentions special preconditions or constraints, for example the consideration of special electrode diameters. In these cases the conditions will be checked, discussed and, if necessary, alternatives are suggested.

2.1.1. <u>TARGET 1</u>: How is the SLAG's resistance if the electrode is moved?

In this first target, the calculations will base in a furnace (resistance mode) with the next disposition.

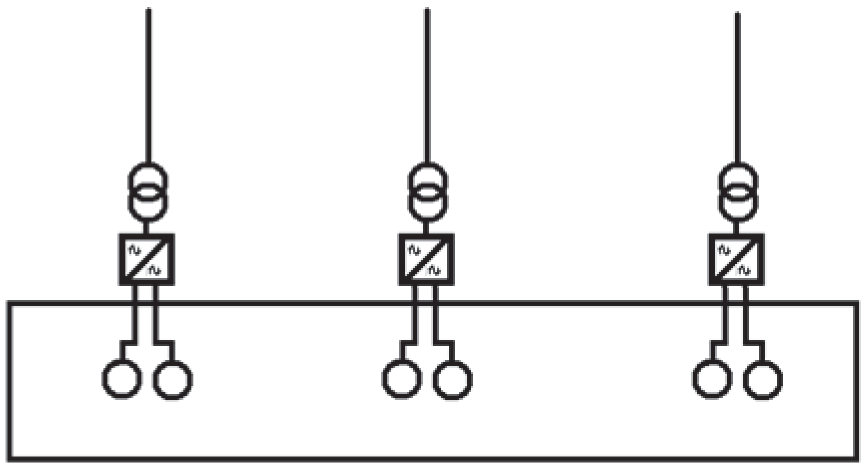


Figure 11. Simplified furnace system

In a zoom in one of the electrode's couple we can see the dimensions to the problem.

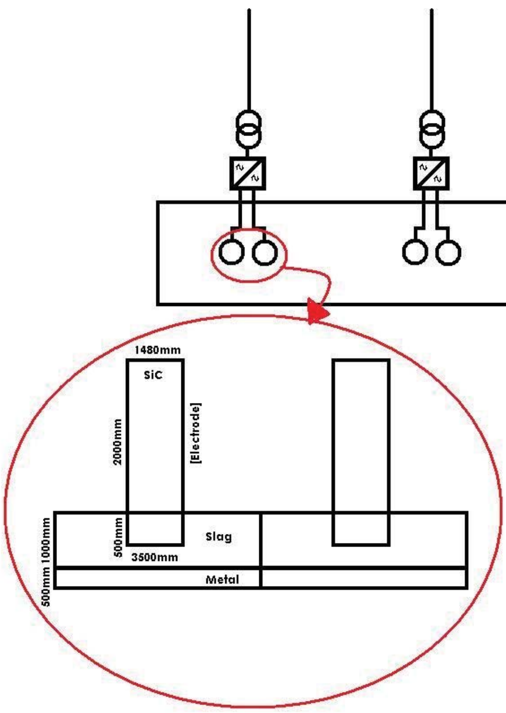


Figure 12. Zoom electrodes in furnace system

Preprocessor:

After define graphically the furnace, start to define in FEMM, in asymmetric mode, in this study, 6 files will be create depend on the electrode position. This files are in the CD added, called *t1_200_800, t1_300_700, t1_400_600, t1_500_500, t1_600_400* and *t1_700_300*.

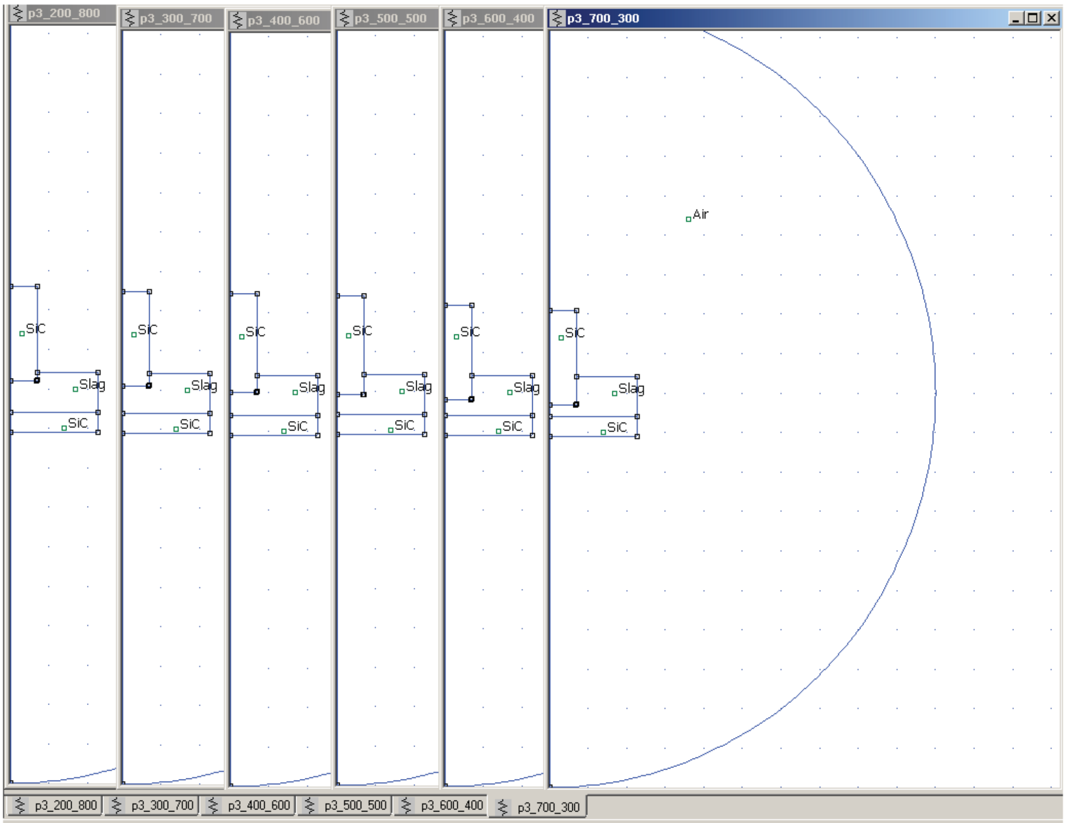
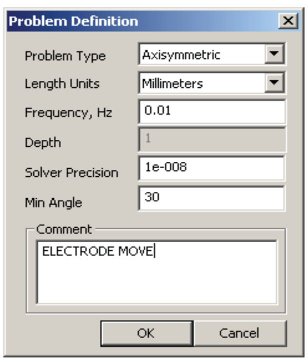


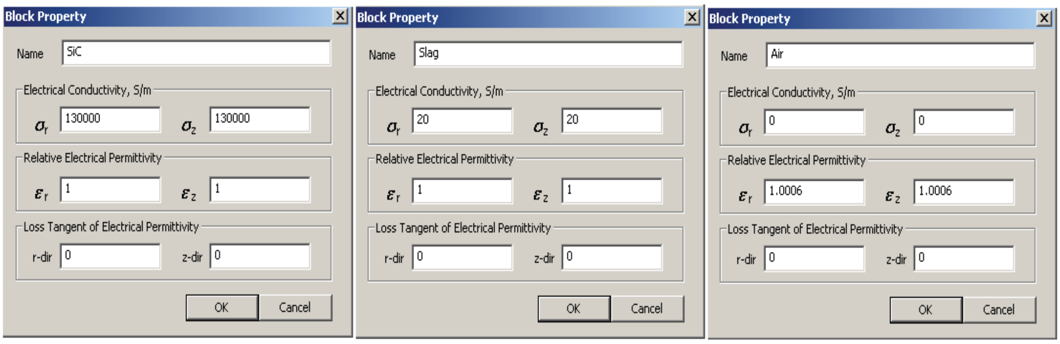
Figure 13. Superposition of files with different electrode position

Whit the next problem characteristics for all of them:

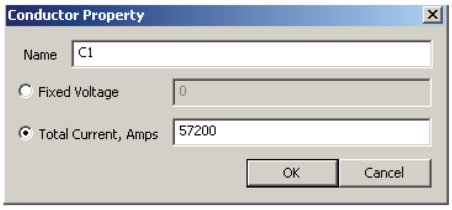


The other characteristic to define are:

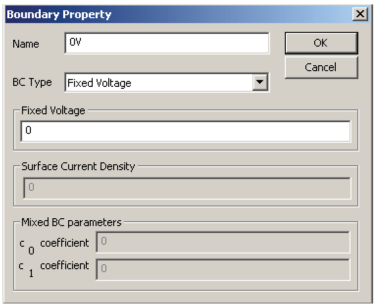
- Material Characteristics:



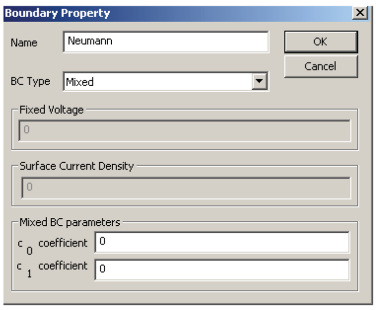
- Conductor Characteristics: (Defined in the top-up of the electrode)



- Boundary Characteristics:



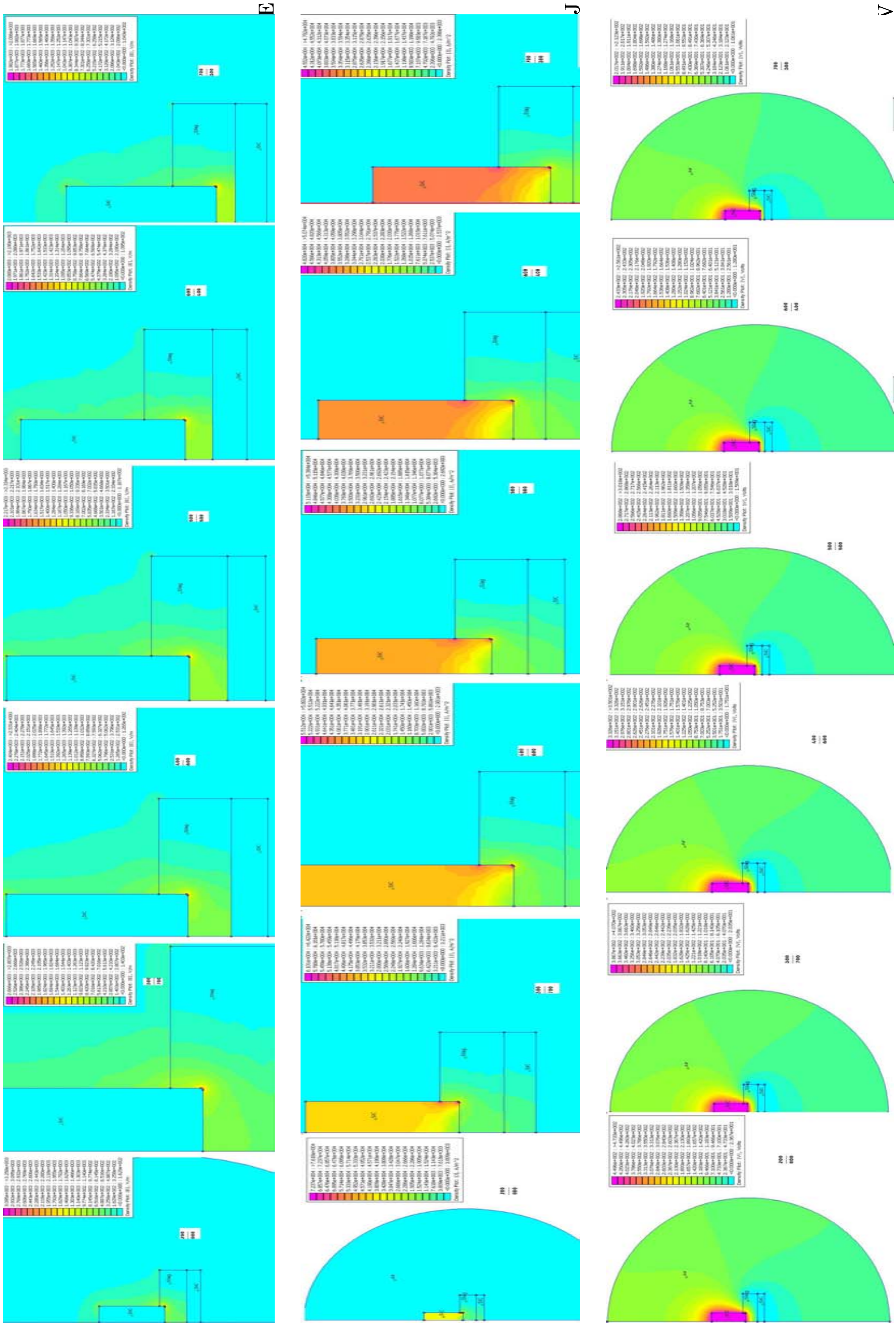
In the edge between both systems slag.



Main boundary with radio of 10.000 mm.

Postprocessor:

The results for E, J and V in the systems are:



E
J
V

The goal in this fist target is obtain the Resistance in the Slag for the different position of the electrode, for this calculate, the next equation is used:

$$R = \frac{2\,P_{SLAG}}{|I_{OUT\ ELECTRODE}|^2} \tag{1.1}$$

In order to obtain the P_{SLAG}, integrates the slag area and to obtain the $I_{OUT\ ELECTRODE}$ integrates the edges of electrode into the slag; all the results are expressed in a EXCEL page added. [electrode&slag.xlsx], below too:

200-800mm		
473,3 V		
62335,9	7843,78	j A
1,35E+07 W		
62827,4567 A		
0,00684840 OMH		
Itotal=57200A		

500-500mm		
302,1 V		
59371,7	52166,5	j A
8,62E+06 W		
79033,806 A		
0,00275987 OMH		
Itotal=57200A		

300-700mm		
407 V		
-60629,4	23643,6	j A
1,16E+07 W		
65076,4471 A		
0,00548815 OMH		
Itotal=57200A		

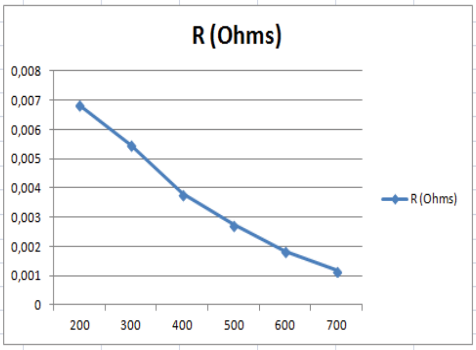
600-400mm		
256,1 V		
-59200,6	66375,8	j A
7,30E+06 W		
88940,7548 A		
0,00184682 OMH		
Itotal=57200A		

400-600mm		
350,1 V		
-61551,8	38110,4	j A
9,99E+06 W		
72394,9354 A		
0,00381223 OMH		
Itotal=57200A		

700-300mm		
212,3 V		
-59583,5	81530,2	j A
6,05E+06 W		
100982,013 A		
0,00118715 OMH		
Itotal=57200A		

All this results in a table and a graphic are:

R (Ohms)	Electrode Deep (mm)
0,0068484	200
0,00548815	300
0,00381223	400
0,00275987	500
0,00184682	600
0,00118715	700

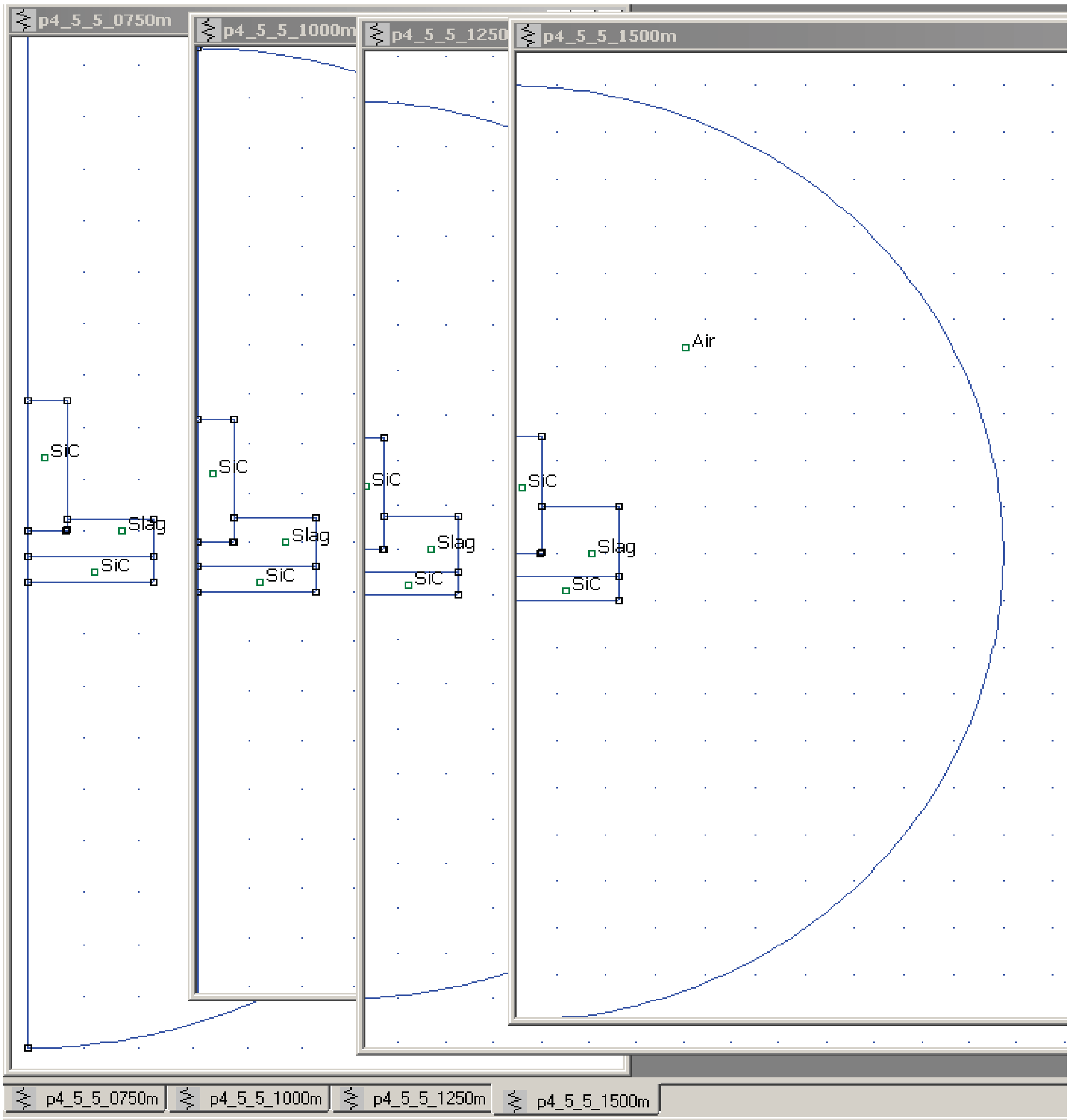


By way of conclusion, it is observable that the Resistance in the slag decrease when the electrode is more deep into the slag, obviously because there is more contact area.

2.1.2 TARGET 2: How could be the SLAG's resistance if the amount of SLAG increases or decrease?

In the same furnace, with the same dimensions that furnace in TARGET 1 (2.1.2).

The same way that TARGET 1 (2.1.2) in order to pre-processor, the difference is in the change of slag amount, between 750mm and 1500mm. For this simulation were created 4 files saved in the CD added, called t2_500, t2_750, t2_1000, t2_1250 and t2_1500. In FEMM the 4 models are the next:



The problem characteristics, the material (SiC, Slag, Air) and Boundaries are the same that in TARGET 1 (2.1.2).

Postprocessor:

In order to obtain the R_{SLAG}, the equation 1.1 is used too, using the P_{SLAG} and the current out the electrode. The results of the calculates are in a EXCEL page [electrode&slag.xlsx], and here:

750mm			
374	V		
-60938,3		13586,8	j A
1,07E+07	W		
62434,5861	A		
0,005467977	OMH		
Itotal=57200A			

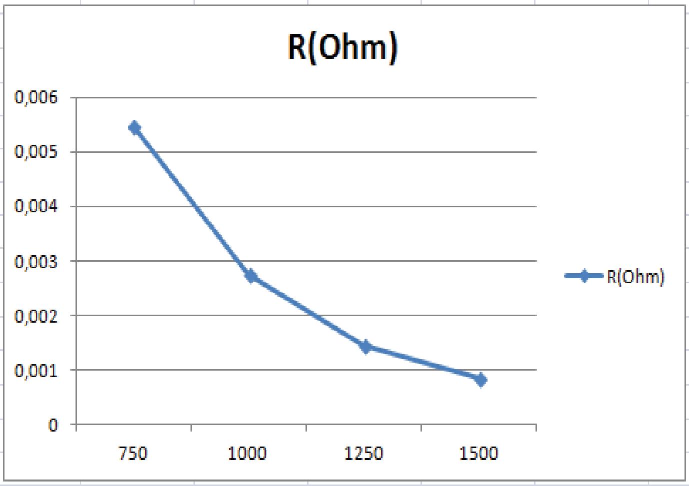
1250mm			
261,7	V		
-58981,8		82641,3	j A
7,47E+06	W		
1,02E+05	A		
0,001448375	OMH		
Itotal=57200A			

1000mm			
302,1	V		
-59371,7		52166,5	j A
8,62E+06	W		
79033,80595	A		
0,002759868	OMH		
Itotal=57200A			

1500mm			
232,3	V		
-56362,1		111036	j A
6,63E+06	W		
1,25E+05	A		
0,000854751	OMH		
Itotal=57200A			

This results in a table and a graphic are:

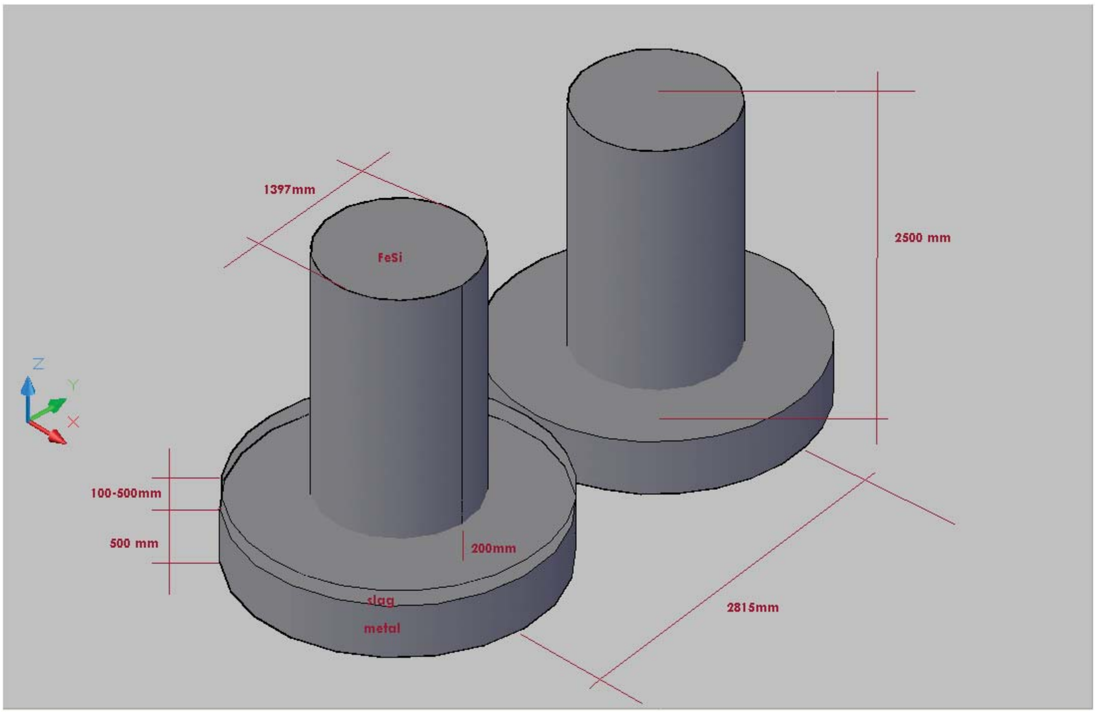
R(Ohm)	z (mm)
0,00546798	750
0,00275987	1000
0,00144867	1250
0,00085474	1500



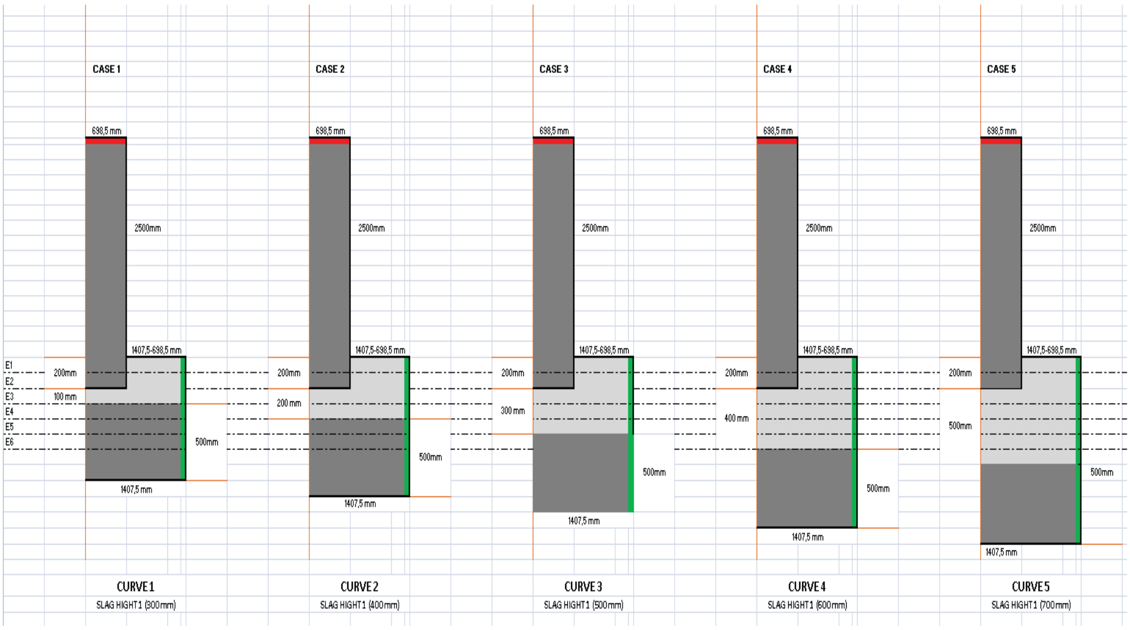
Again the same results, if the slag amount increases the resistance decrease, due to the contact area increase.

2.1.3 <u>TARGET 3</u>: Obtain the position of ELECTRODE and the amount of SLAG for RSLAG=0,6 mΩ

In this target the work is about a new furnace, the same disposition that the last, but different dimensions.

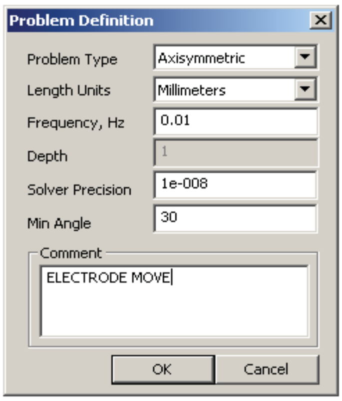


In this target, the variables are slag amount and electrode position, for that, exist 20 possibilities (5 slag amount x 6 electrode positions), graphically the next:



Pre-processor:

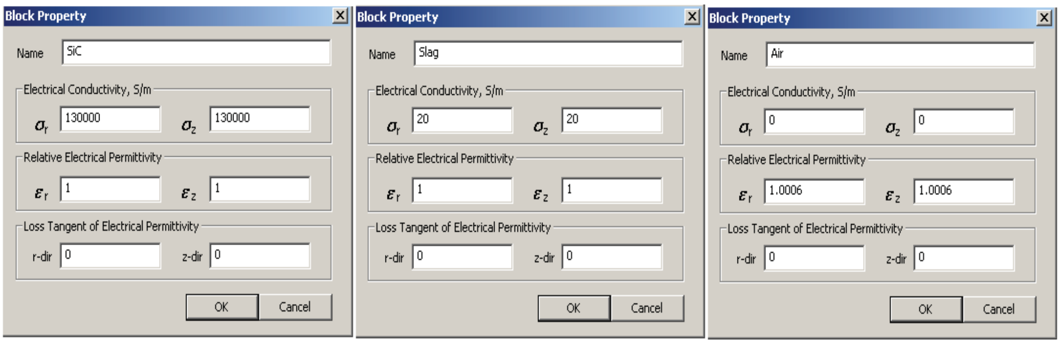
In order to define the problem in FEMM, the next are the characteristics:



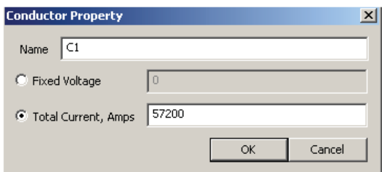
The other characteristic to define are:

- Material Characteristics:

NOTE: SiC and FeSi have similar electric conductivity.

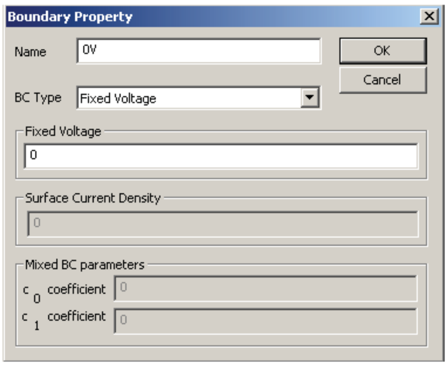


- Conductor Characteristics: (Defined in the top-up of the electrode, in before picture, the red line)

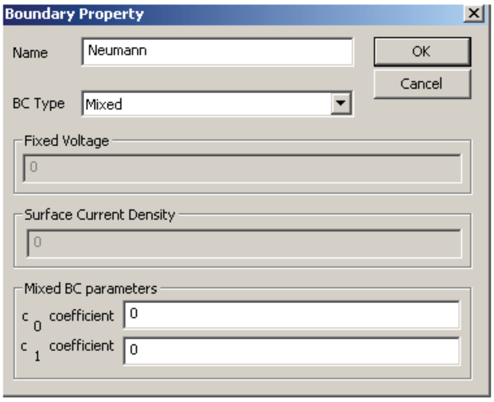


- Boundary Characteristics:

In the edge between both systems slag (in before picture, green line)

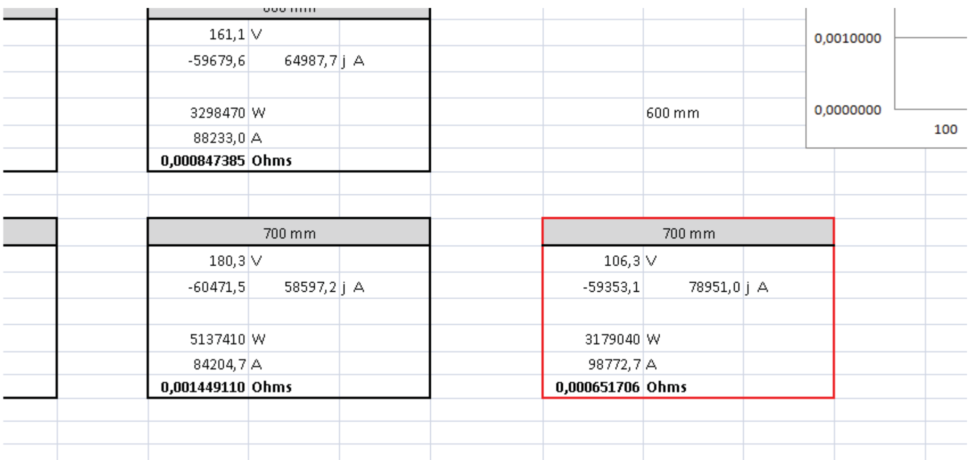


Main boundary with radio of 10.000 mm.



Postprocessor:

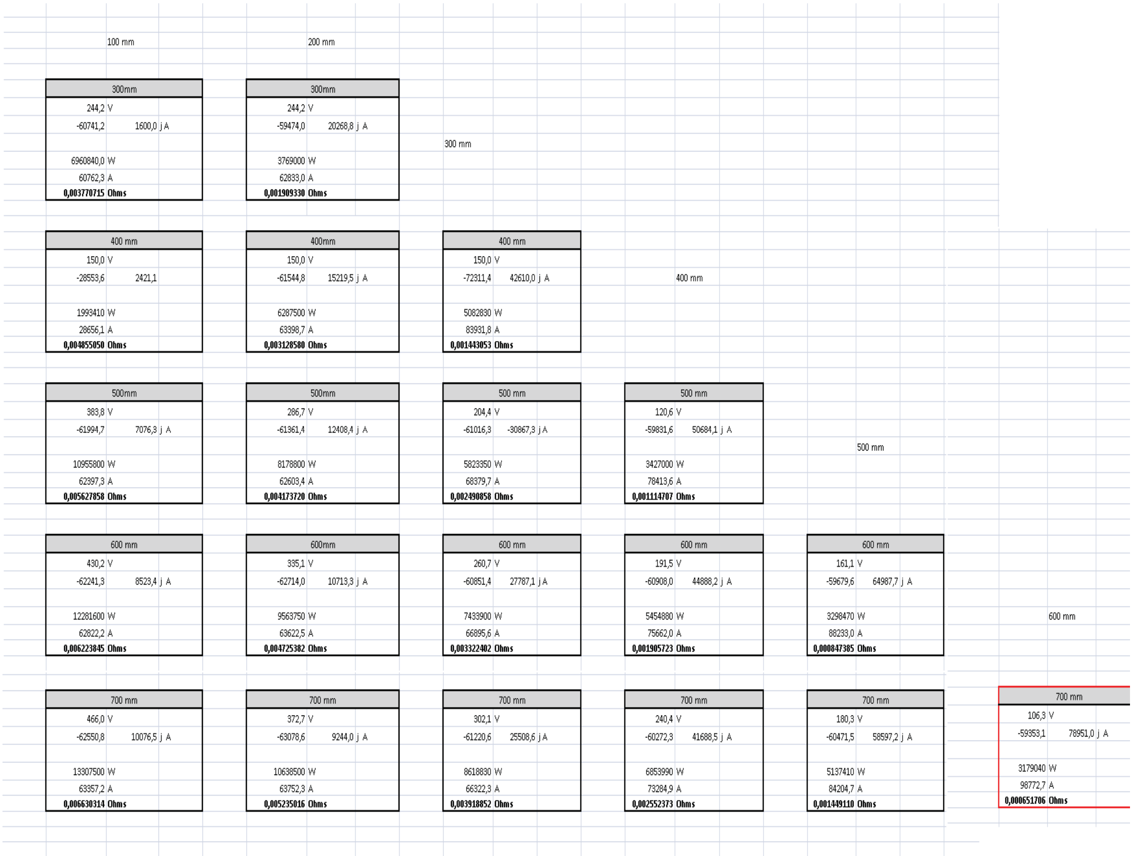
After run all the possibilities, we obtain the result necessary when the R_{SLAG} is 0,6mΩ, this happened in the last movement, when the amount of slag is 700 mm and the electrode is in the lower position, in 600 mm into the slag.



2.1.4 TARGET 4: Create a graphic R SLAG = f (Electrode position, Slag Amount)

This last target in the furnaces is referred to TARGET 3 (2.1.3), with all the data obtained in these, a new graphic is created, this new graphic will have 5 different curves depend on the slag amount (300, 400, 500, 600 and 700 mm), the Axis X will be the electrode position and Axis Y will contain the Resistance obtained in Slag.

All the results are in an EXCEL page added to this project [NewFurnace.xlsx], here showed:


100 mm
200 mm

300mm
244,2 V
-60741,2 1600,0 j A
6960840,0 W
60762,3 A
0,003770715 Ohms

300mm
244,2 V
-59474,0 20268,8 j A
3769000 W
62833,0 A
0,001909330 Ohms

300 mm

400 mm
150,0 V
-28553,6 2421,1
1993410 W
28656,1 A
0,004855050 Ohms

400mm
150,0 V
-61544,8 15219,5 j A
6287500 W
63398,7 A
0,003128580 Ohms

400 mm
150,0 V
-72311,4 42610,0 j A
5082830 W
83931,8 A
0,001443053 Ohms

400 mm

500mm
383,8 V
-61994,7 7076,3 j A
10955800 W
62397,3 A
0,005627858 Ohms

500mm
286,7 V
-61361,4 12408,4 j A
8178800 W
62603,4 A
0,004173720 Ohms

500 mm
204,4 V
-61016,3 -30867,3 j A
5823350 W
68379,7 A
0,002490858 Ohms

500 mm
120,6 V
-59831,6 50684,1 j A
3427000 W
78413,6 A
0,001114707 Ohms

500 mm

600 mm
430,2 V
-62241,3 8523,4 j A
12281600 W
62822,2 A
0,006223845 Ohms

600mm
335,1 V
-62714,0 10713,3 j A
9563750 W
63622,5 A
0,004725382 Ohms

600 mm
260,7 V
-60851,4 27787,1 j A
7433900 W
66895,6 A
0,003322402 Ohms

600 mm
191,5 V
-60908,0 44888,2 j A
5454880 W
75662,0 A
0,001905723 Ohms

600 mm
161,1 V
-59679,6 64987,7 j A
3298470 W
88233,0 A
0,000847385 Ohms

600 mm

700 mm
466,0 V
-62550,8 10076,5 j A
13307500 W
63357,2 A
0,006630314 Ohms

700 mm
372,7 V
-63078,6 9244,0 j A
10638500 W
63752,3 A
0,005235016 Ohms

700 mm
302,1 V
-61220,6 25508,6 j A
8618830 W
66322,3 A
0,003918852 Ohms

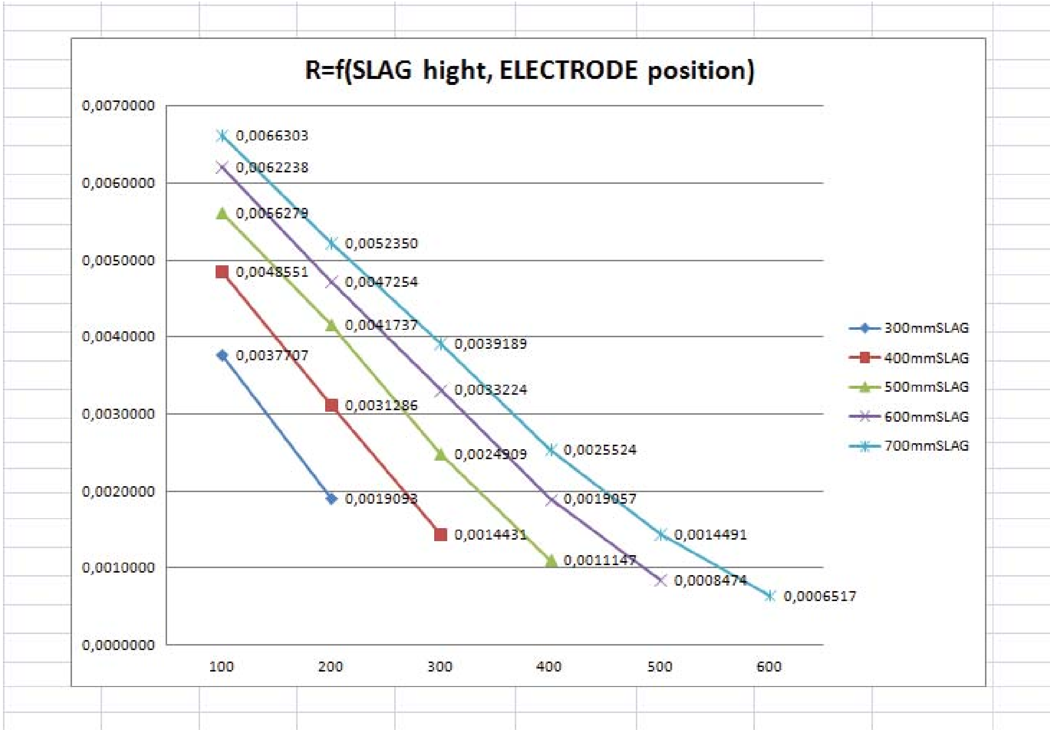
700 mm
240,4 V
-60272,3 41688,5 j A
6853990 W
73284,9 A
0,002552373 Ohms

700 mm
180,3 V
-60471,5 58597,2 j A
5137410 W
84204,7 A
0,001449110 Ohms

700 mm
106,3 V
-59353,1 78951,0 j A
3179040 W
98772,7 A
0,000651706 Ohms

All expressed in a table and the main graphic:

Ei	300mmSLAG	400mmSLAG	500mmSLAG	600mmSLAG	700mmSLAG
100	0,0037707	0,0048551	0,0056279	0,0062238	0,0066303
200	0,0019093	0,0031286	0,0041737	0,0047254	0,0052350
300		0,0014431	0,0024909	0,0033224	0,0039189
400			0,0011147	0,0019057	0,0025524
500				0,0008474	0,0014491
600					0,0006517



As in the other target, the resistance in the slag decrease when de electrode is deeper into the slag and if the slag amount is bigger the resistance decrease more.

2.2 CABLES

In this new section all the problems will base in a system of three cables, 3phasic system, with the next characteristics:

[http://www.kmi.co.id/products/lv-power-cables/copper-cables/121.html]

NYY 1 x (1.5-800) mm² 0.6/1 kV

NYY 1 x (1.5-800) mm² 0.6/1 kV

Cu / PVC / PVC

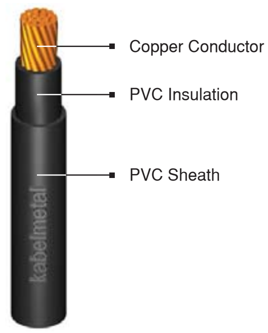
(Copper Conductor, PVC Insulated, PVC Sheathed)
Standard Specification : IEC 60502-1

Construction Data

Nom. Cross Section Area	Overall Diameter	Cable Weight
	approx.	approx.
mm²	mm	kg/km
1.5	6.1	53
2.5	6.6	67
4	7.6	94
6	8.1	117
10	9.1	166
16	10.1	229
25	11.9	345
35	13.0	444
50	15.0	600
70	16.9	815
95	19.1	1,079
120	21.0	1,325
150	23.0	1,604
185	25.5	2,020
240	29.0	2,636
300	32.0	3,219
400	35.5	4,087
500	39.5	5,213
630	44.0	6,712
800	48.5	8,368

Application :
Power cable : Indoors, cable trunking, outdoors and burried in the ground, for power stations, industry and switchgear as well as for urban supply networks, if mechanical damage is unlikely.

Special Features on Request :
- Fire Resistance
- Oil Resistance
- UV Resistance
- Flame Retardant Cat. A, B, C
- Flame Retardant Non Category
- Heat Resistance
- Anti Termite
- Anti Rodent
- Low Smoke Zero Halogen
- Nylon Coated



Note :
Conductor Shape
1.5 - 10 sqmm supplied in solid (re) or non compacted circular stranded (rm)
16 sqmm supplied in non compacted circular stranded (rm) conductor shape
25 - 800 sqmm supplied in non compacted circular stranded (rm) or compacted circular stranded (cm) conductor shape

Standard Packing
1.5 - 10 sqmm supplied in coil @ 100 m
16 - 300 sqmm supplied in wooden drum @ 1000 m
400 - 800 sqmm supplied in wooden drum on available length
Length Tolerance per drum ± 2%

Electrical Data

Conductor			Inductance		Current - Carrying Capacity at 30° C *				Short circuit current at 1 sec
Nom. Cross Sect.	DC Resistance at 20°C	AC Resistance at 70°C	Trefoil formation	Flat formation	in air	in ground	in air	in ground	
	Max.	Max.			Max.	Max.	Max.	Max.	Max.
(mm²)	(Ω/km)	(Ω/km)	(mH/km)	(mH/km)	(A)	(A)	(A)	(A)	(kA)
1.5	12.1	14.478	0.459	0.505	21	27	21	27	0.17
2.5	7.41	8.866	0.423	0.470	27	35	28	35	0.29
4	4.61	5.516	0.404	0.450	37	46	38	45	0.46
6	3.08	3.685	0.380	0.426	46	57	48	57	0.69
10	1.83	2.190	0.350	0.396	64	76	65	76	1.15
16	1.15	1.376	0.327	0.374	84	98	87	97	1.84
25	0.727	0.870	0.312	0.358	114	127	117	125	2.88
35	0.524	0.627	0.299	0.345	140	152	144	150	4.03
50	0.387	0.464	0.290	0.336	172	180	177	178	5.75
70	0.268	0.321	0.280	0.326	218	220	225	218	8.05
95	0.193	0.232	0.274	0.321	270	264	278	260	10.93
120	0.153	0.184	0.269	0.315	315	300	325	296	13.80
150	0.124	0.150	0.266	0.313	362	336	373	331	17.25
185	0.0991	0.121	0.264	0.310	420	379	433	374	21.28
240	0.0754	0.093	0.261	0.307	503	439	518	432	27.60
300	0.0601	0.075	0.258	0.305	580	494	598	486	34.50
400	0.0470	0.061	0.256	0.302	674	558	695	549	41.20
500	0.0366	0.049	0.252	0.299	781	629	806	618	51.50
630	0.0283	0.041	0.247	0.293	901	704	930	692	64.89
800	0.0221	0.035	0.242	0.289	1018	775	1052	762	82.40

** Further information about rating factor for certain cable arrangement can be found on supplementary technical information*

Leiterdurchmesser nach VDE 0295 (DIN EN 60228)

Die in der Tabelle angegebenen Werte für den Leiterdurchmesser sind nach VDE 0295 (DIN EN 60228) je nach Nennquerschnitt und Leiterklasse aufgeführt.

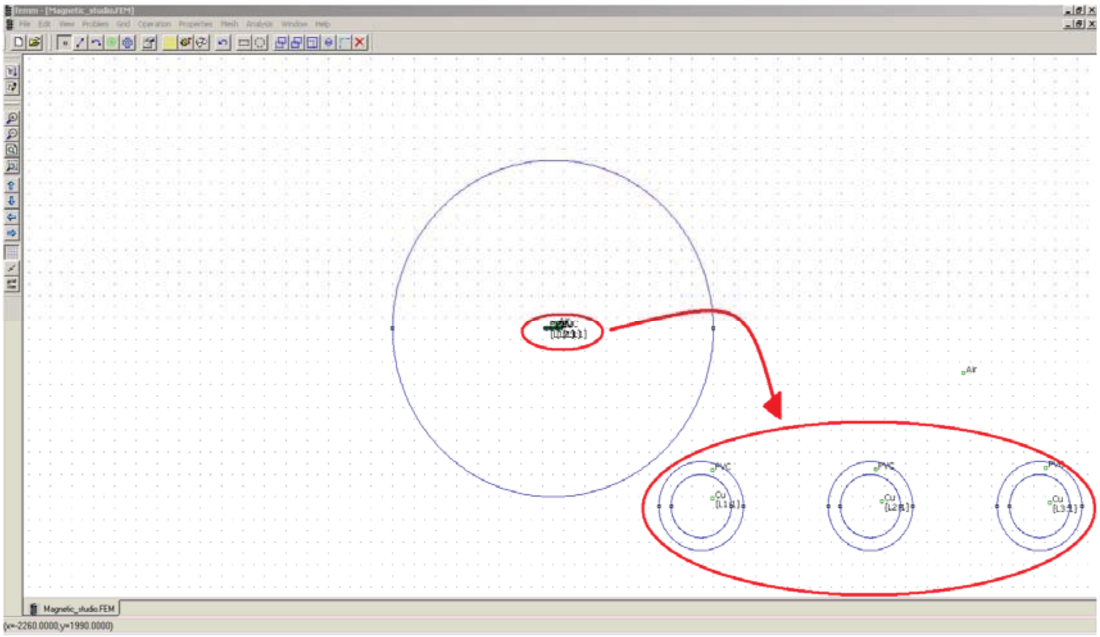
Einadrige Rundleiter (Cu und Alu) **Klasse 1**			Mehrdrähtige Rundleiter unverdichtet (Cu) **Klasse 2**	Fein- und feinstdrähtige Cu-Leiter **Klasse 5 und 6**
Nennquerschnitt mm²	min-ø[3] mm	max-ø mm	max-ø mm	max-ø mm
0,5	–	0,9	1,1	1,1
0,75	–	1,0	1,2	1,3
1	–	1,2	1,4	1,5
1,5	–	1,5	1,7	1,8
2,5	–	1,9	2,2	2,4
4	–	2,4	2,7	3,0
6	–	2,9	3,3	3,9
10	–	3,7	4,2	5,1
16	–	4,6	5,3	6,3
25	5,2[1]	5,7[2]	6,6	7,8
35	6,1[1]	6,7[2]	7,9	9,2
50	7,2[1]	7,8[2]	9,1	11,0
70	8,7[1]	9,4[2]	11,0	13,1
95	10,3[1]	11,0[2]	12,9	15,1
120	11,6[1]	12,4[2]	14,5	17,0
150	12,9[1]	13,8[2]	16,2	19,0
185	–	15,4	18,0	21,0
240	–	17,6	20,6	24,0
300	–	19,8	23,1	27,0
400	–	22,2	26,1	31,0
500	–	–	29,2	35,0
630	–	–	33,2	39,0
800	–	–	37,6	–
1000	–	–	42,2	–

[1] nur für Aluminium-Rundleiter,
[2] für mineralisolierte Rundleiter, nur für Kupfer
[3] min-ø für Cu-Rundleiter nicht festgelegt

2.2.1 <u>TARGET 5</u> : **Magnetic problem, calculate the total heat losses in the conductors.**

Pre-processor:

Open a new Magnetic Problem in FEMM, start drawing the problem, showed in next figure:



Dimension of the system:

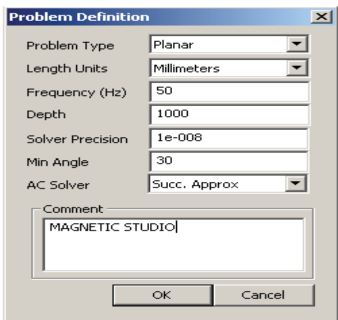
$Ø_{CONDUCTOR}$ = 20.6 mm

$Ø_{PVC}$= 29 mm

Distance between centre of cables = 29mm

$Ø_{BOUNDARY}$= 3000 mm

Problem characteristics:

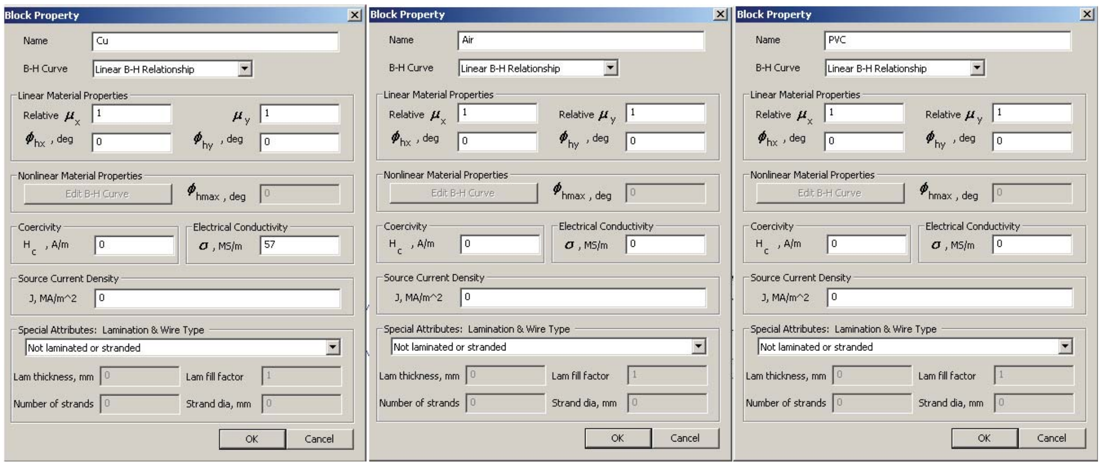

Problem Definition

Problem Type	Planar
Length Units	Millimeters
Frequency (Hz)	50
Depth	1000
Solver Precision	1e-008
Min Angle	30
AC Solver	Succ. Approx

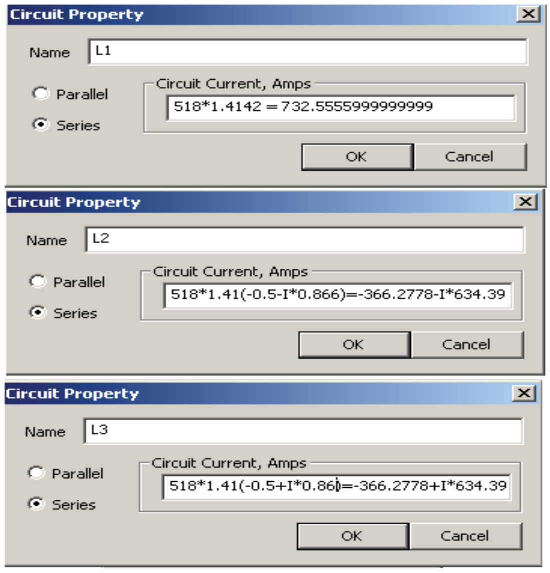
Comment
MAGNETIC STUDIO

OK Cancel

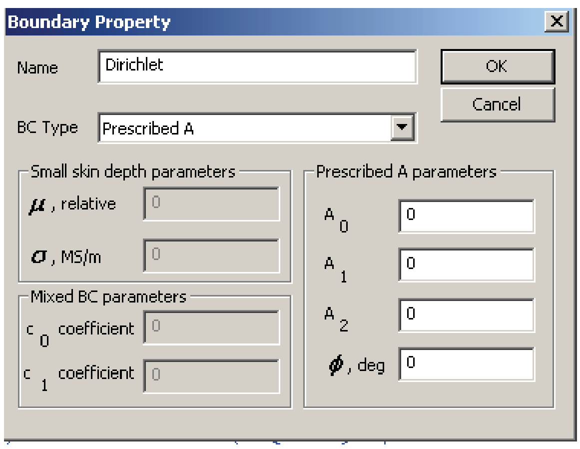
Material Properties:



Conductors Properties:

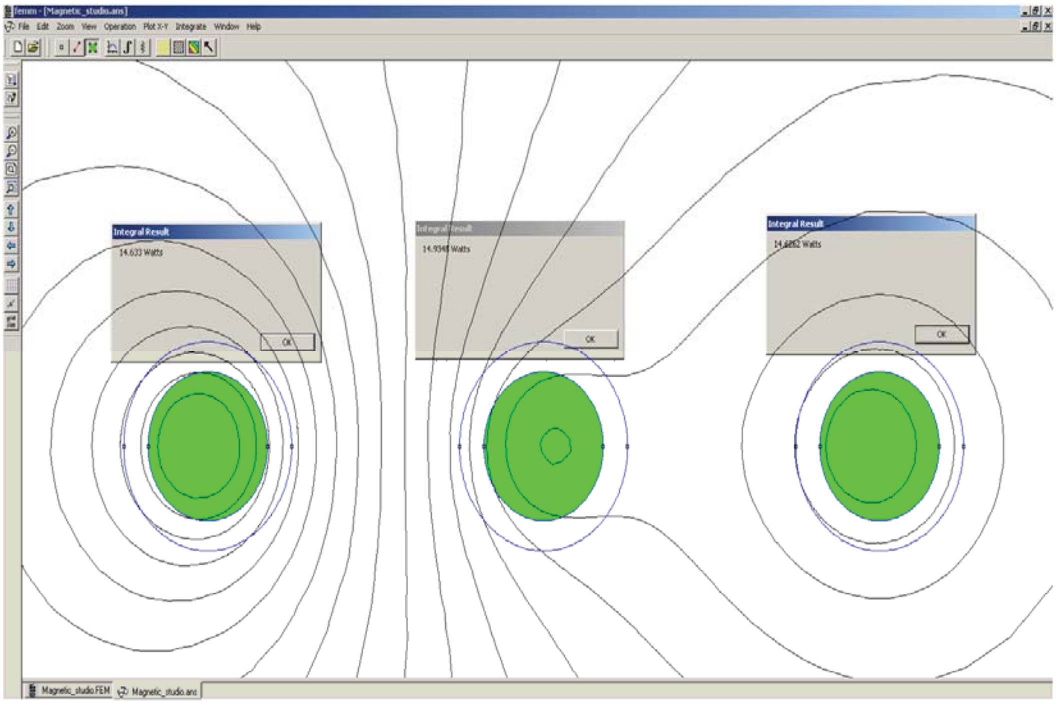


Boundary properties:



Post processor:

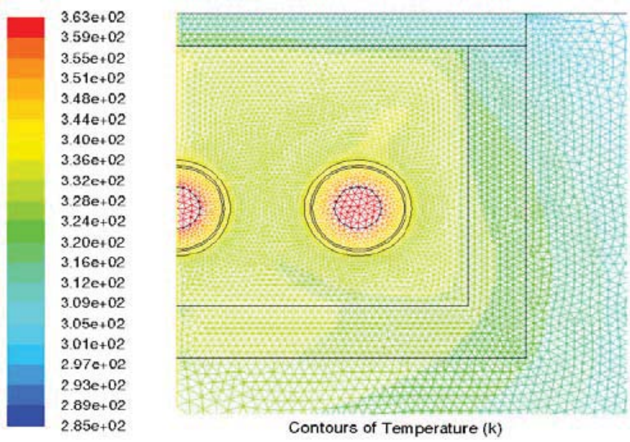
After run the described system, the losses in the conductors are obtained:



In total, in all conductors the total losses are: 44.194 W/m

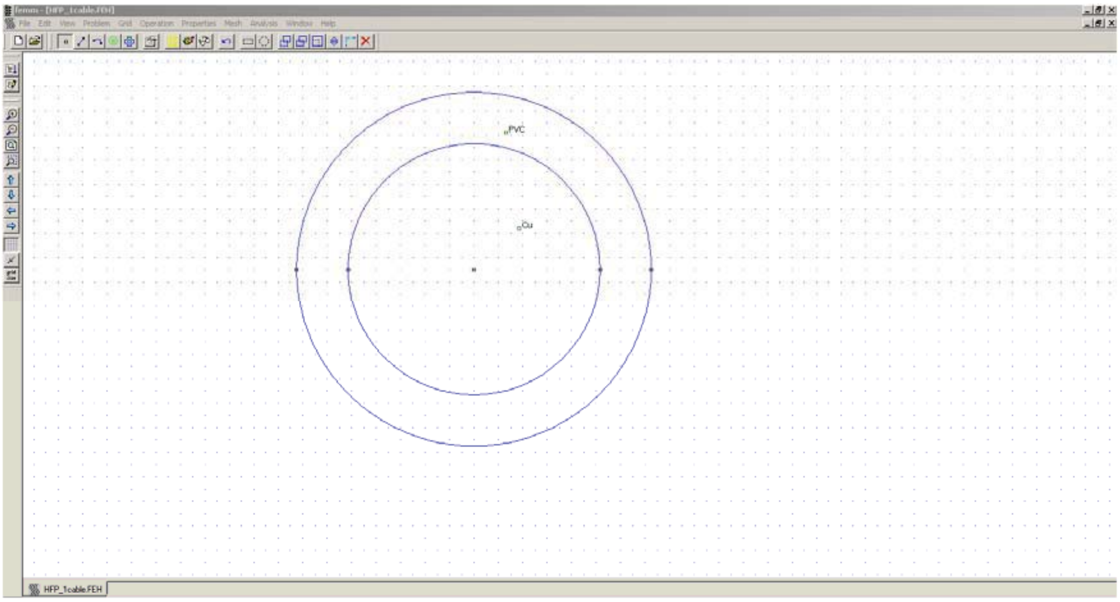
2.2.2 <u>TARGET 6</u>: Heat flow problem, calculate temperature distribution inside a cable.

For have a first impression and compared the next results is interesting read or made a mention to an article about this simulations, in "*Circuit Rating Methods for High Temperature Cables" from University of Southampton* there are many references useful in this work. In the mentioned article there is the next simulation, the same that the expected.

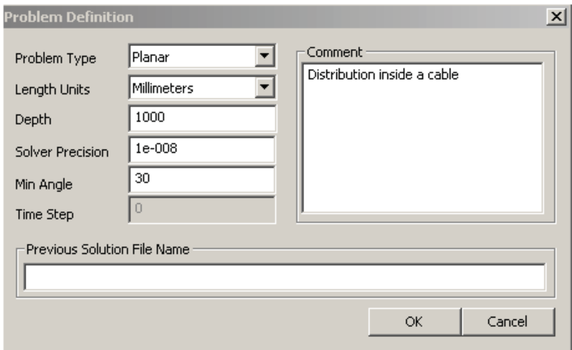


Pre-processor:

Using a cable from the last simulation, but now in a Heat Flow Problem, the new file is created, *HFP_1cable*.



The problem definition is a basic heat flow problem.



Material properties:

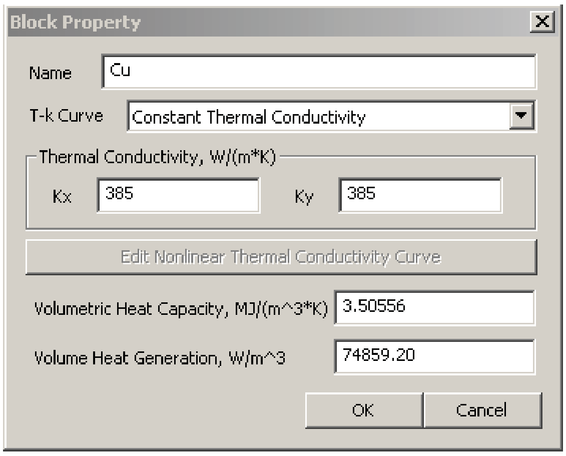
In this case is important, calculate the Volumetric Heat Capacity and Volume Heat Generation in Copper.

$$\boldsymbol{Volumetric\ Heat\ Capacity} = 393\ \frac{J}{kg\ K}\ x\ 8{,}92\ \frac{kg}{dm^3}\ x\ 10^3\ \frac{dm^3}{m^3} = \mathbf{3,5}\ \frac{\boldsymbol{MJ}}{\boldsymbol{k\ m^3}}$$

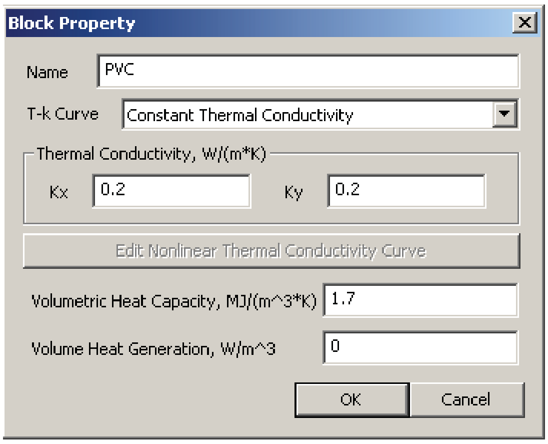
The current in the conductor is 518 A and the R_{AC} = 0.093 mΩ/m at 70ºC the "real losses" (in simulation are theoretical, not based in experiences) are:

$$P = I^2 * R = 518^2 * 0.093 = \mathbf{24{,}95}\ \text{W/m}$$

$$\boldsymbol{Volume\ Heat\ Generation} = \frac{Total\ Losses}{Area} = \frac{24{,}95}{\pi\ (10{,}3mm)^2} = \mathbf{74.859{,}20}\ \frac{\boldsymbol{W}}{\boldsymbol{m^3}}$$



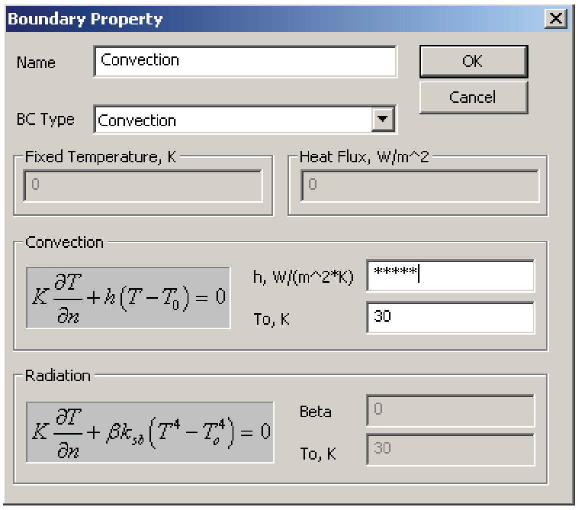
The same form for PVC:



And in the last step, the boundary properties, a new kind of boundary will be defined in this section, a convection boundary, this boundary is characterised by:

$$\lambda\, \nabla T = h\ (T - 30)$$

expressed in the box dialogue, here T_O is known, it is 30º but h is the Heat Transfer coefficient, and is a experience data, for that, the calculations will be based in this parameter h.

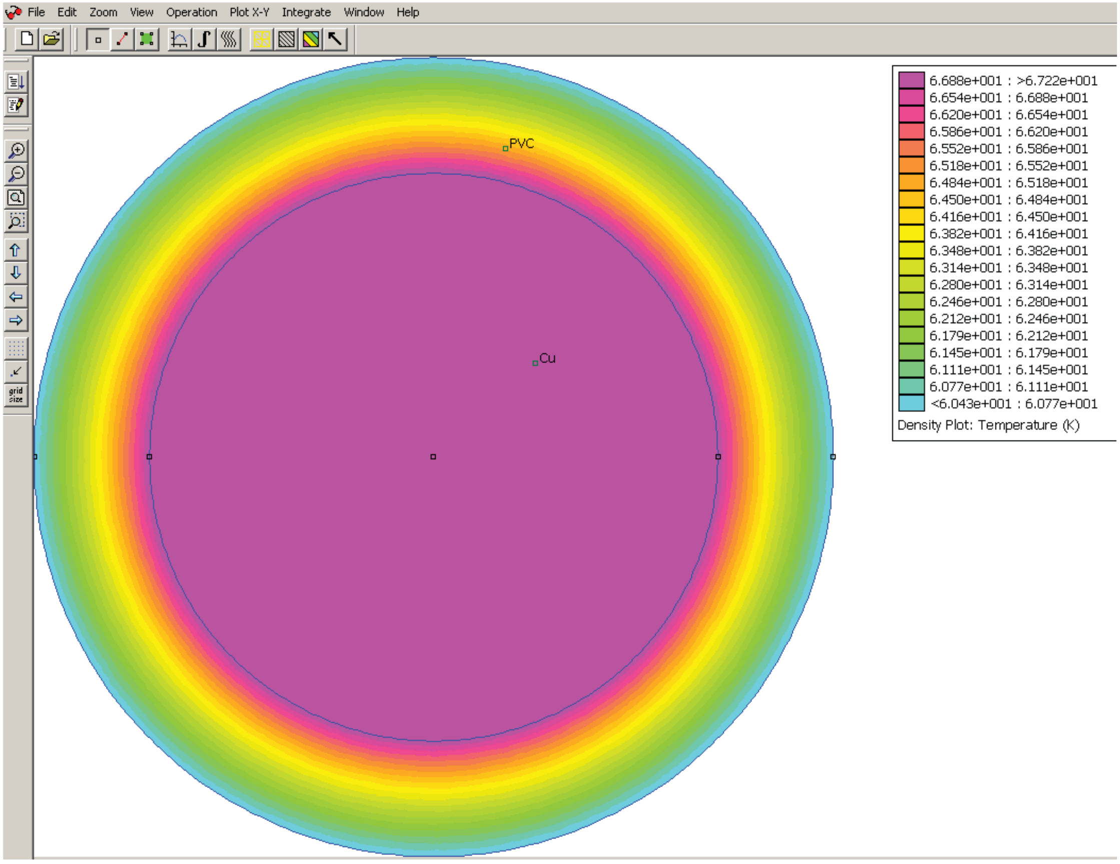


Postprocessor:

The next table is obtained in function of different h values:

h (W/m² K)	Tmax (K)	Tmin (K)
5	91,2	84,8
7	75	69
7,5	73	66,5
9	66,9	60
10	63,8	57,8
12	59,2	53

With h=9 have the best distribution, graphically the next:



3. REFERENCES.

[1] FEMM User's Manual. Version 4.2 David Meeker

[2] Design of modern Large Capacity FeNi smelting plant. R. Deger, J. Kempken, J.Kunze and R.König.

4. AGENDA

AGENDA

15/11/2012
- ✓ First meeting
- ✓ **FIRST TARGET:** Read the FEMM's manual and practise with a furnace the common tools of the program. Remember the Magnetic theory.

26/11/2012
- ✓ New article about work with furnaces.
- ✓ **TARGET 1:** How is the SLAG's resistence if the electrode is moved?

03/12/2012
- ✓ **TARGET 2:** How could be the SLAG's resistence if the amount of SLAG increase or decrease?

11/12/2012
- ✓ Check the results of TARGET 1 and 2, that must be done again.

17/12/12
- ✓ Check the results of TARGET 1 and 2 again.
- ✓ **TARGET 3:** Whit a new Furnace, obtain the position of ELECTRODE and the amount of SLAG for R_{SLAG}=0,6 mΩ.

17/01/2013
- ✓ Check the results of TARGET 3.
- ✓ **TARGET 4:** Create a graphic, that show, R_{SLAG}=f(Electrode position, Slag Amount)
- ✓ Introduction to cables theory
- ✓ **TARGET 5:** Magnetic problem, calculate the total heat losses in the conductors.
- ✓ **TARGET 6:** Heat flow problem, calculate the temperature distribution.

23/01/2013
- ✓ Check TARGET 4 AND 5
- ✓ In TARGET 5 there are some problems whit the distribution of the temperature, for that we continues whit calculates.

30/01/2013
- ✓ Check TARGET 6

07/02/2013 ✓ Check all objectives

14/02/2013 ✓ Exposition complete work.