ADVANCED MODELLING AND BAKING OF ELECTRODES

RP Meyjes, J Venter and U Van Rooyen

Metix (PTY) LTD, Johannesburg, South Africa; info@metix.co.za

ABSTRACT

A finite element model of a Söderberg electrode was developed for in-house development of stronger, more reliable electrodes and electrode equipment. The fully coupled approach, as described below, is used for optimal accuracy and interaction between physics. Although similar models have been used for quite some time to predict paste baking, casing stress distribution etc. all of these models assumed no separation between the casing and paste, or between the casing and the contact shoe. This model is set apart from previous models by the fact that separation is allowed and simulated, and the results in this paper will show that the separation affect the heat and current flow paths with considerable amounts.

1. INTRODUCTION

Strong well baked electrodes are crucial in the production of Ferro Alloys, and warrants continuous development to increase their reliability and efficiency. Although the use of Finite Element Analysis in this development process has been documented before, recent advances in computational, as well as software technology, provides the ability to take these analyses to the next level in terms of model complexity. The model in this paper includes various phenomena which have been excluded from previous studies.

Previous models presented at conferences used the “weak coupled” method of solution. In this method a Thermal-Electrical analysis is performed in which the temperature distribution in the electrode is determined. These temperatures are then applied to the next model, in order to solve thermal expansion, together with the structural loads and boundary conditions, and the deformations in the model is solved and presented as the results. It does not allow for changes in heat flow and current flow paths caused by structural deformation and hence separation.

Using the fully coupled method, as in this paper, allows for more accurate calculation and allows all relevant degrees of freedom to influence each other. The degrees of freedom are Temperature, Voltage and Displacements (TEMP, VOLT, UX, UY and UZ).

This model has been developed to:

- Understand the working of an electrode system.
- Improve casing and contact shoe design.

This paper will cover the following aspects of electrodes:

- Baking profiles and the effect various parameters have on this.
- Separation between casing and paste as well as between the casing and contact shoe.

Advances made in this model, over previous FEA models, include:

- Separation is allowed between the casing, paste and contact shoe.
- Automatic switching between conduction and radiation as a means of heat transfer when separation occurs.
- Finer mesh density allows for higher quality results, especially on the casing.
- Fully coupled analysis, which means that displacement of any component will change the heat and current flow paths as well.

The electrode primarily consist of a carbon aggregate and a tar binding, called the paste, contained by a thin steel casing with a number of fins welded to the inside. A contact shoe, which presses against the outside of the casing, supplies the electrical current.

The electrode paste is initially a non conductive mixture, which will turn into a soft mixture from 60°C and then bake from 450°C to form the solid electrode. The 450°C isotherm is where the baking zone is initiated, and is of significant importance in this model, as it will be used as a measure to compare various models with each other. The electrode paste will continue to bake up to 1500°C and the electrical and thermal conductivity will increase with temperature, until it approaches that of graphite when well baked.

The top level of the softened paste is known as the liquid level, and is measured from the top of the electrode, but expressed as the level above the top of the contact shoe. Some operations prefer to measure it from the bottom of the contact shoe.

As the electrode is consumed in the furnace, it is slipped at a rate of up to 0.5 m/day. The casing is extended at the top by welding on extra pre-fabricated casing sections and more paste cylinders are added to continue the electrode forming.

The mantle surrounds the casing above the heat shields. A fan supplies air from the top of the mantle to sustain a positive pressure in the annulus between the casing and the mantle, preventing furnace gas and dust leakage into the furnace building. In some furnaces a heater is installed to heat the air and assist the melting of the paste. The furnace in discussion has a 3 element heater with heating capacities of 6 kW per element.

The aim of any development on electrode systems is to move the baking zone higher into the contact shoes to ensure a stronger electrode, and avoid hard and soft breakages. A break is considered a hard break when parts of the baked carbon break off and fall into the furnace. Soft breakages take place when the entire baked part, and sometimes the entire electrode falls into the furnace. Soft breakages are also called green breaks. By moving the initiation of baking as high as possible into the electrode, the electrode will be stronger at the point where it slips out of the contact shoe, and the casing is consumed by the intense heat in the furnace, thus preventing breaks in the electrode.

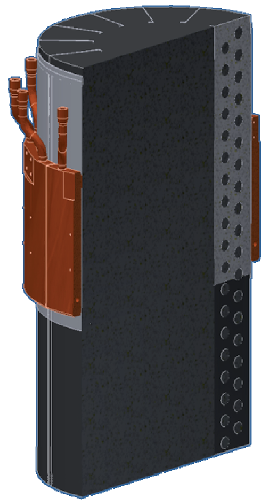


Figure 1: A section through the modelled electrode

2. MODEL

The model on which this paper is based is a 1.5m diameter electrode with 8 contact shoes, each spanning 45°, and with 16 fins per casing. The casing thickness is 3.5mm. A 22.5° sector is modelled, to reduce computational effort, resulting in half a contact shoe and one fin on the casing. Since the casing is not guided and is free to rotate about its own axis, the position of the fin is arbitrary and in this model it will be placed so that two fins are situated symmetrically on a single contact shoe.

3. SEPARATION

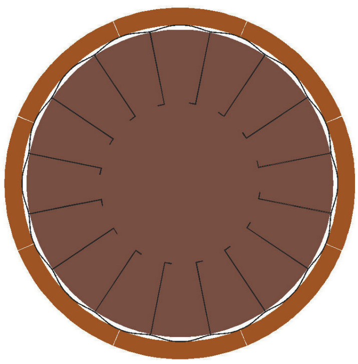


Figure 2 - Expected deformed shape

The separation between the casing and paste as well as between the casing and the contact shoe is due to the thermal expansion of the casing. The casing is anchored in the paste by the lip at the end of the fins and the holes through the fins, which constrain the radial expansion of the casing. The constraint cause the casing to expand irregularly and this in turn cause the separation between the casing and the contact shoe. The significance of this separation is that the heat transfer method changes from conduction, when in contact, to radiation when not in contact. Radiation is a less effective method to transfer heat, and as such, less heat is lost to the contact shoe cooling water, which in turn improves the baking of the electrode.

To model this phenomenon contact elements are overlaid on the contact surfaces between the various components. These elements allow compressive stress to be transferred, but in tension it will separate. Additionally these elements check the contact status and adjust the heat transfer method accordingly.

Figure 2 shows the expected deformed shaped on a cross section just above the lower edge of the contact shoe, to indicate the expected deformed shape with separation included.

4. AC VS. DC

Although the furnace in discussion is an alternating current (AC) furnace, the model is setup to solve using direct current (DC). This is to reduce computational effort and allow for more complex modelling of other phenomena. The effect of AC vs. DC is discussed in detail in various papers, most notably by Halldr Plsson et al. [1] and by H.L Larsen [2] in 3D and 2D respectively. The conclusion drawn by Halldr was that the proximity effect results in almost three times higher heat generation at the maximum point than at the minimum point of an electrode surface. It must be noted that both these models did not include any components other than the electrodes themselves, and thus the simplicity of these models allowed for the calculations in discussion.

Three electrodes are arranged in triangular fashion in a circular furnace. As discussed by Innvaer et al [3], the tangential heat distribution will not be symmetrical throughout the electrode, due to higher temperatures in the central delta of the furnace, but due to computational constraints, it is not modelled in this model and this phenomenon will be ignored in this paper.

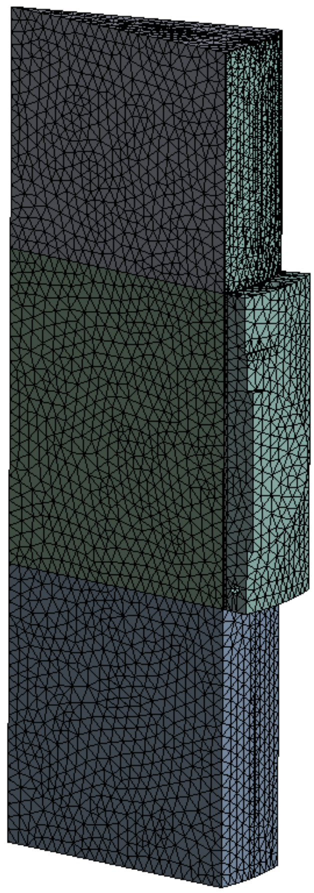


Figure 3: Mesh used in simulation

5. BOUNDARY CONDITIONS

On this model the structural boundary conditions (BC) are as follows:

- A pressure BC is applied to the pressure area on the back of the contact shoe. The applied pressure is calculated so that the initial contact pressure exerted by the contact shoe on the casing is 1.35 bar.
- The top edge of the casing is constrained in the axial direction of the electrode, simulating the effect of the slipping device.
- The contact shoe is constrained from movement in the axial direction of the electrode.

The thermal boundary conditions are:

- Water flow of 2.5 m/s through a Ø30 mm channel in the contact shoe is simulated through the use of a convection boundary condition of 8300 W/m^{2}K at 35 °C water temperature. These are typical design values used in the development of Metix contact shoes.
- Convection of 50 W/m^{2}K at 1300°C is applied to the exposed areas of the electrode protruding below the contact shoe.
- Convection of 100 W/m^{2}K at 35°C is applied to the external faces of the casing above the contact shoe, simulating air flow inside the mantle.
- The surface temperature of the burden is considered to be 800°C. Radiative exchange takes place between this surface and the exposed areas of the paste below the contact shoe. No radiation takes place to the contact shoe’s external faces, as this is covered by the pressure ring (not modelled) in the furnace.
- A convection of 30 W/m^{2}K at 60°C is used to simulate the natural convection of the top surface of the paste exposed to atmosphere.

Electrical boundary conditions are:

- A current flow of 108 kA through the electrode.

- Voltage supplied at 210 V at the water inflow area of the contact shoe.

6. MESH

The mesh used in this analysis is depicted in Figure 3. It consist of 165 000 nodes and 85 000 elements. ANSYS [4] coupled field elements are used for all solid bodies, and contact areas are overlaid with Contact elements.

7. MATERIAL PROPERTIES

Temperature [°C]	Mild Steel (Casing)	Copper (Contact shoe)	Electrode Paste (Electrode)
Electrical Conductivity [$\Omega^{-1}.m^{-1}$]			
20	6.25×10^6	58.8×10^6	
100	4.54×10^6	41.7×10^6	0.1×10^6
			0.11×10^6
500	1.639×10^6	32.36×10^6	0.13×10^6
1000			0.17×10^6
1400			0.20×10^6
1800			0.25×10^6
2200			0.30×10^6
2600			0.38×10^6
Thermal Conductivity [$Wm^{-1}K^{-1}$]			
20	52.0	380	
100	51.0	370	
200			3.2
500	39.3	300	6.8
1000			19.2
1400			30.3
1800			37.1
2200			40.2
2600			38.9
Young's Modulus [GPa]			
20	200	130	3.3
Poisson Ratio			
constant	0.3	0.34	0.15
Linear Coefficient. Of Thermal Expansion [$m.m^{-1}K^{-1}$]			
0 - 100	17.0×10^{-6}	17.0×10^{-6}	
0 - 300	17.3×10^{-6}	17.3×10^{-6}	
0 - 500	17.3×10^{-6}	17.5×10^{-6}	
500 - 800			-11.6×10^{-6}
800 - 1000			-2.5×10^{-6}
1000 - 2500			4.3×10^{-6}
Density [$kg.m^{-3}$]			
	7870	8300	1342
Yield Strength or 0.2% Proof Stress [MPa]			
20	300	450	17. (compressive)

Table 1: Material Properties of the Metals and Carbon [**5**]

8. RESULTS

For the boundary condition as described in section 5 above, the results are depicted below. This is referred to as the reference model, and will be used for comparisons in the study of the effects of various parameters.

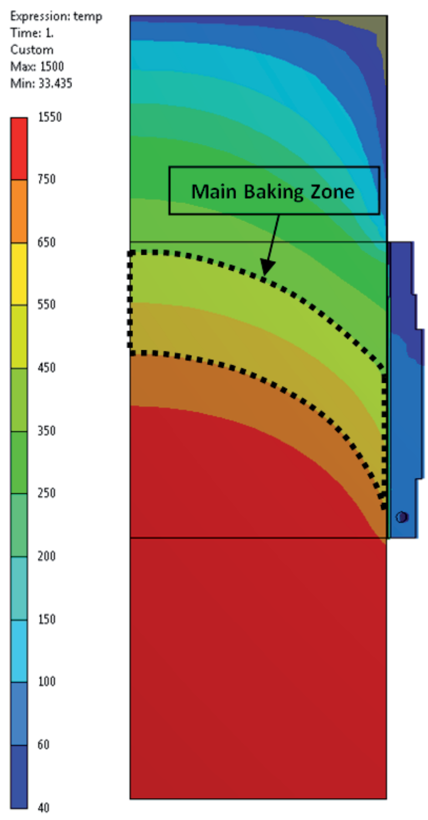


Figure 4: Temperature on symmetry plane

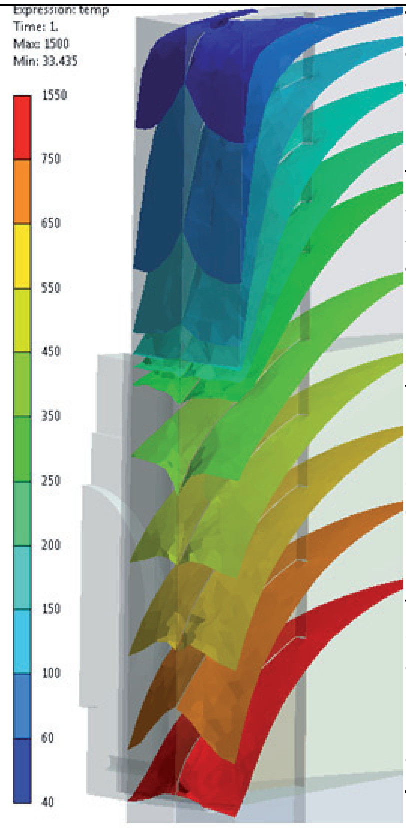


Figure 5: Isotherms in electrode

The two figures to the left depict the temperature distribution in the model.

Figure 4 shows the temperature on the symmetry plane, thus on a section through the centre of the contact shoe, while Figure 5 show the isotherms in the electrode clearly indicating the effect that the steel casing's higher thermal conductivity has on thermal flux. This can be compared to Figure 6, which shows a simular result to Figure 4, but with no separation allowed in the model between the components of the electrode system

In Figure 7 below, an expanded view of the 450°C and 750°C isotherms in the electrode is shown, the effect of the mild steel casing's higher thermal conductivity can clearly be seen in this figure.

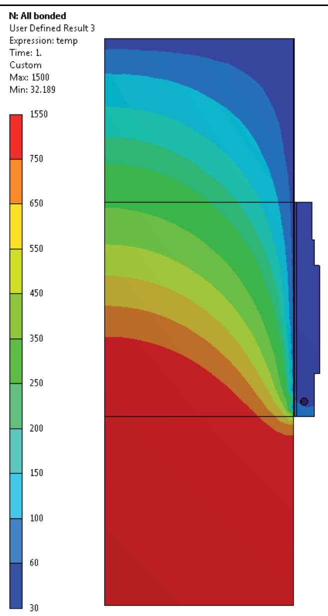


Figure 6: Thermal contours when no separation is allowed

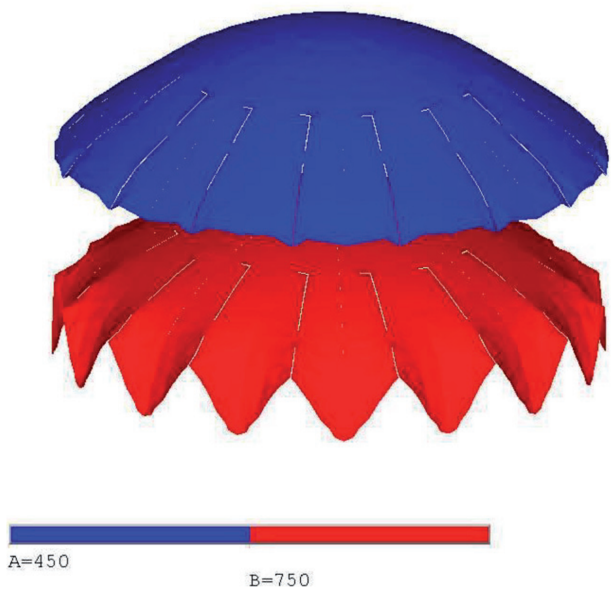


Figure 7: Expanded view of 450°C and 750°C isotherms

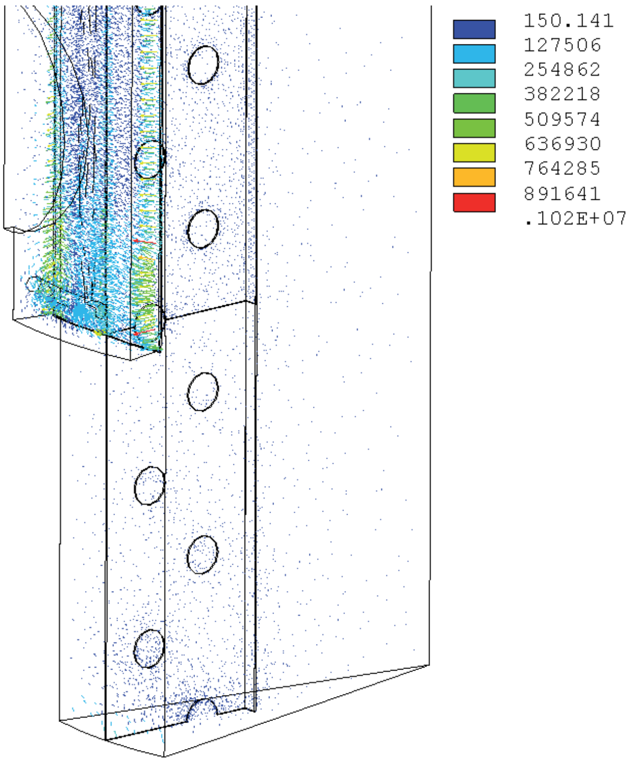
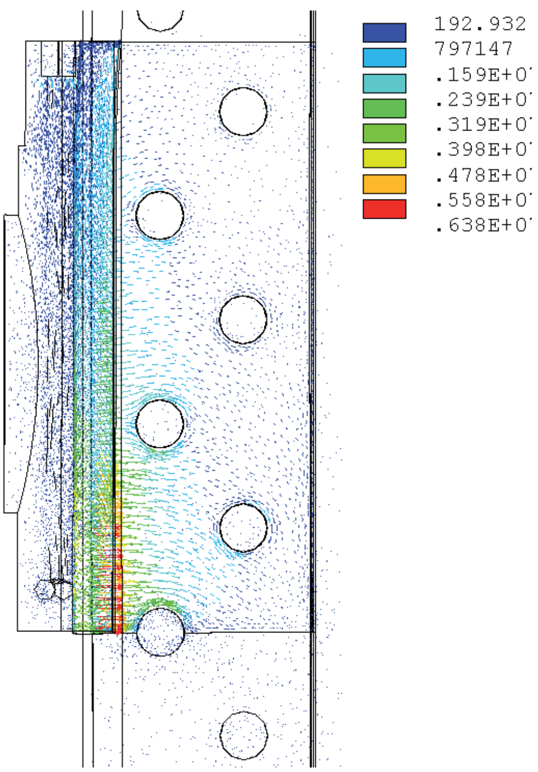


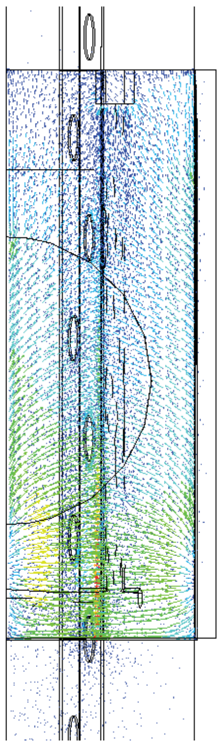
Figure 8 show the heat flux density in W/m^2 in the lower half of the model. The heat flux has the highest value where the contact shoe is in contact with the casing, as this provides the best possible heat flow path.

Traditional wisdom dictates that electrical current will follow the path of least resistance which, in this case, is straight down the contact shoe, due to the good conductivity of the copper, entering the electrode at the bottom of the contact shoe. Figure 9 and Figure 10 prove that this is not the case, because of the separation of the casing and contact shoe, and that the bulk of the current will enter the electrode through the casing in the lower two thirds of the contact shoe.

Figure 11 shows the status of the contact between the contact shoe and the casing, providing an indication of the separated areas. Near contact indicate that the contact areas that are within the pinball region of each other. In this case the pinball region is 10 mm.

Figure 8: Heat flux density (W/m^2)





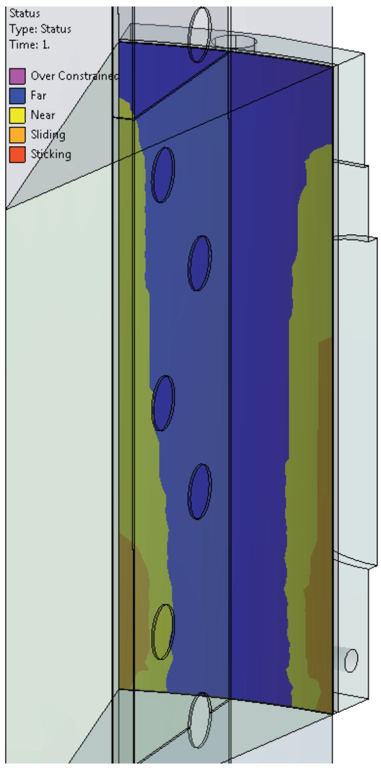


Figure 9: Current Density (A/m^2)

Figure 10: Current Density (A/m^2)

Figure 11: Contact status

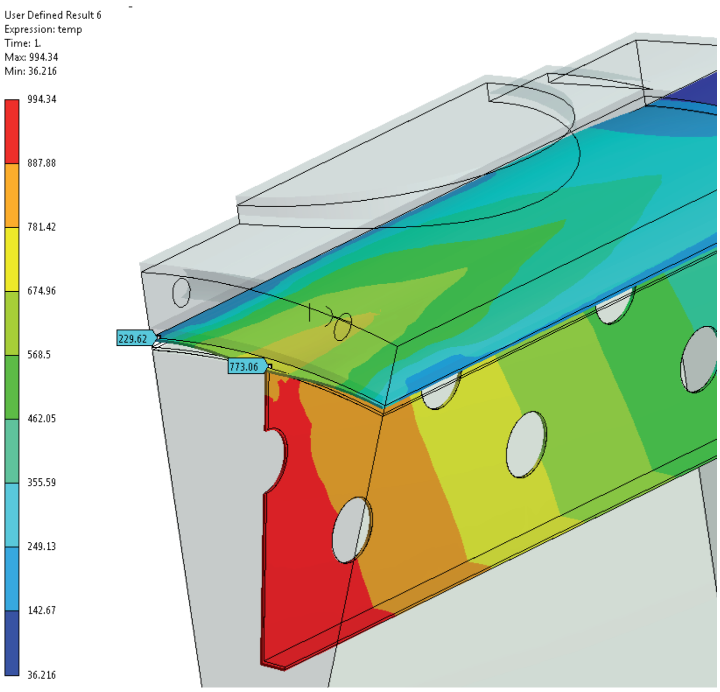


Figure 12: Radial displacement of casing

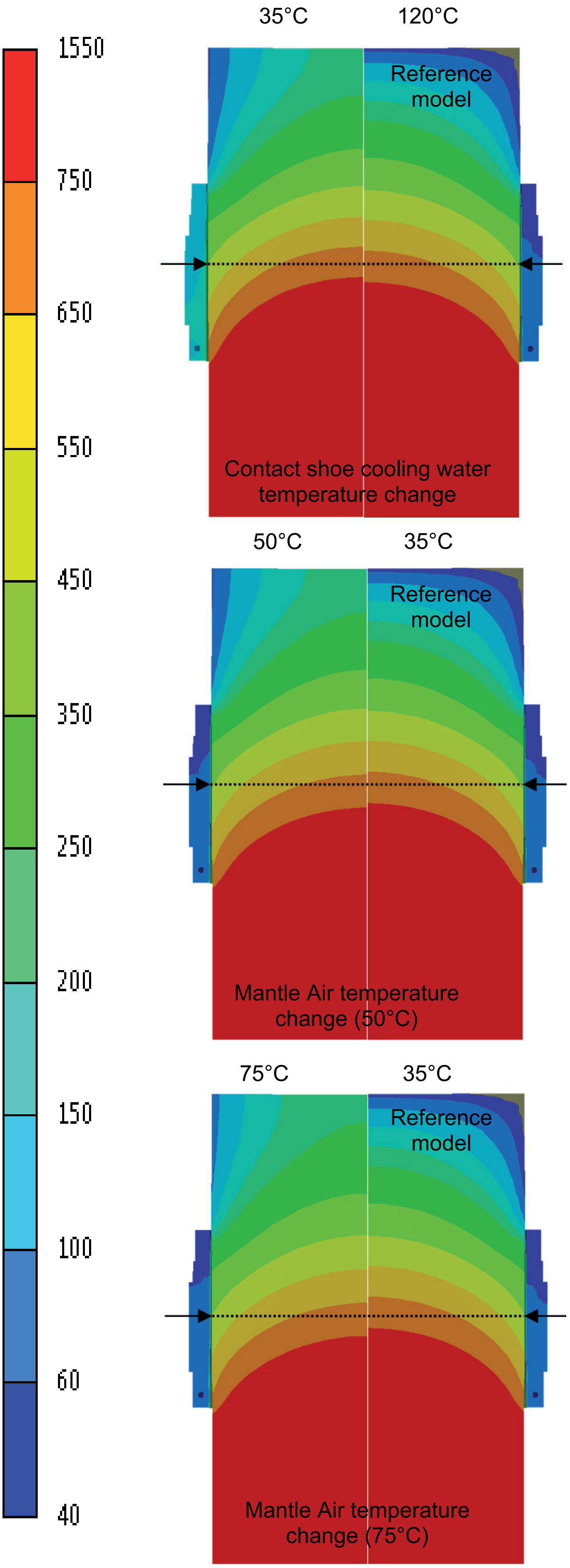
The radial displacement of the casing is shown on a temperature plot in Figure 12. Temperatures in the casing vary from 230°C, where good contact and hence good conduction with the contact shoe is present, to 780°C where there is separation.

The circumferential thermal expansion of the casing, combined with the anchoring effect of the fins, causes the separation between the components, and alters heat and current flow paths as described.

9. PARAMETER STUDY

A study of the effect of various parameters in the model is performed and depicted in this section. For each parameter change the result is compared with the results obtained in Section 0 above. The parameters that were changed are:

- Cooling water inlet temperature from 35°C to 120°C.
- Mantle air temperature from 35°C to 50°C and in another study to 75°C.
- Electrical current from 108 kA to 119 kA (10% increase), 54 kA (halved current) and then lastly, the current is completely removed.

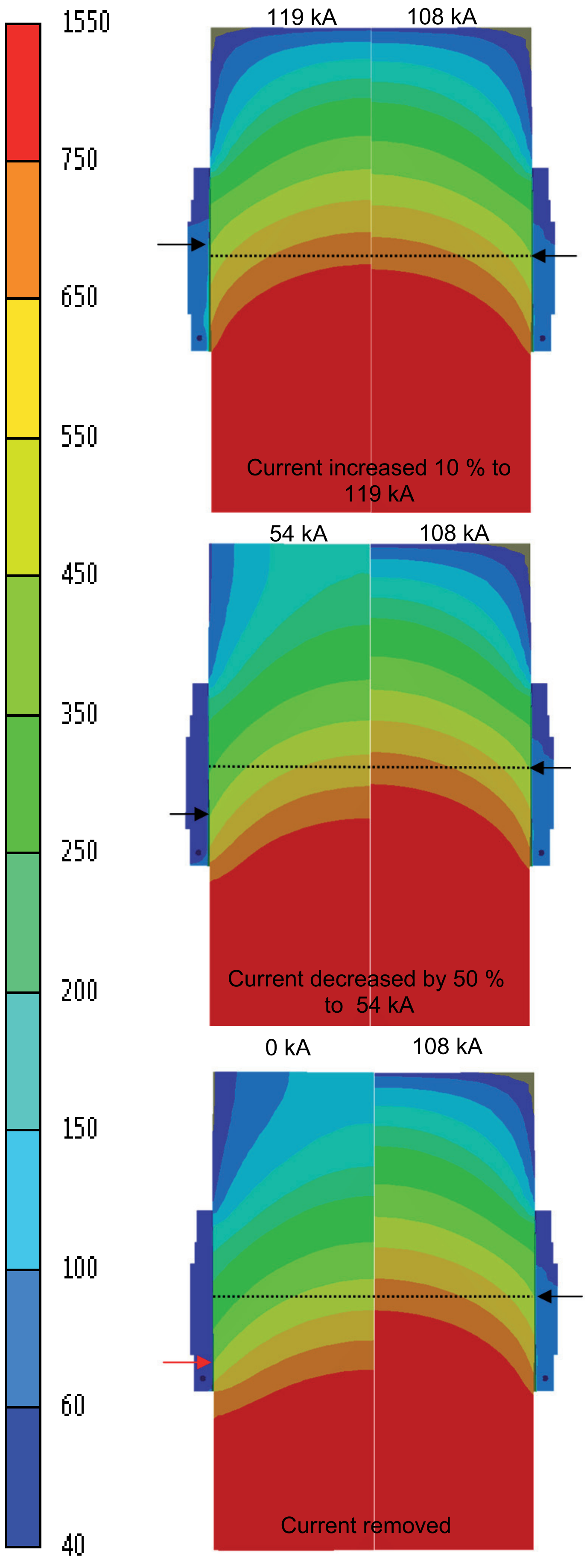


The model to the left represent a change in temperature of the cooling water of 85°C. The reference model utilized contact shoe cooling water with an inlet temperature of 35°C, while the water in the model to the left is 120°C.

The effect is mostly visible in the tempertures of the contact shoe itself, while the location of the 450°C isotherm is mostly unchanged. The arrows indicate where the 450°C isotherm, the lower limit of paste baking, intersect the casing.

The mantle heaters increase the temperature of the air that is supplied to sustain a positive pressure inside the mantle. The main purpose of heating this air is to assist in softening the paste, and thus increasing liquid levels. The two figures to the left shows that there are virtually zero improvement in the location of the 450°C isotherm, as indicated by the arrows on each figure, but that the softening of the paste does benefit from this.

The first figure represents the model where the air temperature was increased from 35°C to 50°C. In the second model, the air temperature is increased to 75°C.



The figures on this page shows the effect that electrical current has on the baking zone. It must be considered that current value has a quadratic effect on the resistive or Joule heating ($Q=I^2R$).

The first figure shows the effect of increasing the current from 108 kA to 119 kA, a 10% increase. This improves (moves it higher into the contact shoe) the location of the 450°C isotherm.

In the second figure the current is halved – from 108 kA to 54 kA. This has a drastic effect on the location of the 450°C isotherm, and lowers it by about one third the length of the contact shoe.

The last figure depicts the effect if the current is completely removed. Although this is not a realistic assumption, it is shown to indicate the effect that resistive heating in the electorode material has on the baking of the electrode. This should be viewed in conjuction with the other two figures on this page.

10. CONCLUSION

The results from this study show that separation between the casing and the contact shoe, as well as separation between the casing and the paste in an electrode, reduces heat transfer from the electrode to the contact shoe cooling water and the surroundings. This in turn improves baking of the electrode, and leads to stronger electrodes. The separation mentioned above also alters the current flow paths significantly from those on a model with no separation.

Other effects that have been investigated, and will influence the location of the 450°C isotherm, include increasing the temperature of the cooling water, the mantle air and the electrical current. Increasing the cooling water temperature from 40°C to 120°C has a negligible effect on the 450°C isotherm, but does increase the contact shoe temperature significantly. The effort required to design and build a system to keep the water under pressure to sustain these temperatures will not justify the improvement in baking.

Increasing mantle air temperature does not assist with baking, but does raise the temperatures in the upper half of the electrode, which will assist with the softening of the paste.

Electrical current has the largest effect of all parameters studied on baking, and only a 10% increase in current will significantly improve the baking of the electrode.

11. REFERENCES

[1] Halldr Plsson and Magns Jnsson, "Finite Element Analysis of proximity effects in Soderberg electrodes", 2000
[2] H.L Larson, "Current distribution in Electrodes of industrial three-phase electrodes electric smelting furnaces", 2006 Nordic COMSOL Conference
[3] Reidar Innvaer, Knut Fidje and Terje Siras, "Three dimensional calculations on smelting electrodes", modelling, Identification and Control, 1987, Vol 8, No 2, 103 - 115
[4] ANSYS, Version 12.0.1, www.ansys.com
[5] I. Mc.Dougall, C.F.R Smith, B. Olmstead and W.A. Gericke, "A finite element model of a Soderberg electrode with an application in casing design", Infacon X, 2004.