TEMPERATURE PROFILES IN SØDERBERG ELECTRODES

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ABSTRACT

Temperatures were measured with K-type thermocouples in two electrodes in an industrial FeMn furnace. The measurements were taken over a period of 16 days with seven measurement days, including one furnace shutdown and start up. The temperature profiles show a temperature rise from 50 to 70° C in the area of the paste level. Further downing of the electrode induced current from the current bars heat up the paste above the contact clamps. Differently positioned measurement points on the circumference of the electrode show large differences in paste temperature. In one measurement position between the fins of the casing, temperatures reach up to 270° C due to induction, and at these temperature volatiles may start to leave the coal-tar pitch going upward through the melted electrode paste. The volatiles may condensate again, and hence decrease the coal-tar pitch viscosity which again increases the chance of segregation in the paste. The highest temperature is found between the steel fins because heat conduction by the steel decreases temperature gradients close to the fins. The need for heat conduction by steel fins can also be seen in a COMSOL computer model where the steel fins are not included, and better heat conduction would improve the model. During high slipping before a furnace shutdown the position of the baking zone is moved down, but stays within the contact clamp. Temperatures in the electrode need more than 12 hours to recover after a shutdown of 8 hours.

1. INTRODUCTION

The Søderberg electrode is made of electrode paste. The electrode paste is a mixture of carbon aggregates (anthracite, coke or scrap graphite) and a binder (coal-tar pitch), and is added into a steel casing on top of the electrode. As the electrode is consumed the electrode and the casing with electrode paste is moved down towards the furnace. The movement of the electrode is called slipping, and the resistive heating from the electrode current and heat from the furnace - heat the new paste. The electrode paste softens as it heats and will fill the whole casing between 50-100°C. The paste is finish baking to a solid carbonaceous body at about 475 °C [1]. Important inputs to electrode quality are raw materials (carbon aggregate and binder), the slipping rate and the electrode current. Too high slipping rate can make the baking zone (450-500° C) move under the contact clamps. This may cause a soft breakage if the electrode current is higher than the current carrying capacity of the electrode casing. Too high slipping rate also reduces the strength of the baked electrode. The electrode current is also the main source of heat for electrode baking and is thus important for the electrode quality. The operating conditions of a ferroalloy furnace will also influence the baking conditions and inferior electrode quality may be the result of unfavourable furnace operation [2].

One of the reasons for the successful invention of the Søderberg electrode in 1919 was the use of fins in the steel casing. Figure *1-1* illustrates the temperature distribution in the Søderberg electrode from addition of paste cylinders to the baked electrode in the smelting zone. The equipment for electrode handling is also shown in Figure 1-1.

One of the most important raw materials in the electrode process is the coal-tar. Coal-tar is a by-product from coke production. The metallurgical coke produced from coal is used in the blast furnace production of steel. In the coking process, the coal is heated to 1000-1200°C with a holding time of 14-20 h. The yield of coke is about 75% and the yield of coal-tar 3-4%. Water and chlorides are then removed before the crude tar is distilled to give coal-tar pitch. From 1 metric ton of coal about 15-20 kg coal-tar pitch is produced [3, 4].Coal-tar pitch is the distillation residue after naphthalene-, creosote- and anthrecene-oils are boiled of. Anthracene oils are the heaviest of the mentioned oil fractions and have boiling point above 300°C. Coal-tar pitches consists of many individual organic compounds, mostly polycyclic aromatic hydrocarbons with 3-6 rings [5]. Distillation of the lighter fraction is an important characteristic of coal-tar pitch used as binder for electrode paste. Components that are vaporized at low temperatures may rise and condensate higher in the electrode column and make the paste more liquid in this area. Distillation is usually checked in accordance with ASTM 2569-97 (withdrawn in 2006) in the range of 270° C to 360° C. For electrode paste little or no volatiles should evaporate at lower temperatures.

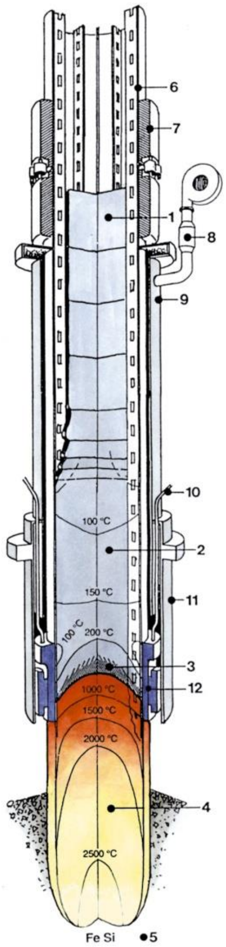

Figure 1-1: Illustration of the Søderberg electrode in a FeSi furnace, from Schei et.al.[6]. Electrode zones and equipment are numbered in the figure: Paste cylinders – 1, Melted paste – 2, Baking zone – 3, Baked electrode – 4. Smelting zone, Casing – 6, Slipping rings – 7, Fans for heating air – 8, Suspension casing– 9, Current tubes – 10, Heat shield -11, Contact clamps – 12.

Using Søderberg electrodes is an efficient way of adding energy to metal producing processes, and hence Søderberg electrodes are used in numerous different processes such as production of ferrosilicon, ferromanganese, ferrochromium, platinum and nickel matte. The furnace process and the process temperature will be different for each process and the temperature gradient in the electrode is believed to change accordingly. This paper will hence describe the temperature profile and the variation in the temperature profile in 1.9 m diameter electrodes during FeMn operation. The maximum operating temperature in FeMn furnaces are believed to be about 1500 °C.

Computer simulations have since the 1970's been used to improve Søderberg electrode management. McDougall et al. [7] used a 3-D model to asses different casing materials and their influence on the baking zone. Meyjes et al. [8] also used modelling as a tool for casing and current clamp design. Larsen et al. [9] used mathematical modelling to understand thermal stresses in electrodes during shutdown and state that temperature measurements are important to validate the computer simulations. Ord et al. [10] studied the electrode equipment influence on electrode temperature by using mathematical simulations in non-ferrous furnaces, and concluded that the effect of contact clamp cooling water is significant.

2. EXPERIMENT

Steel tubes were mounted on the electrode casing to be able to move the thermocouples up and down in the electrode. Oxygen tubes used in the tapping were cut into pieces of 2 m and then screwed back together during welding of new casings. This worked very well without any visible pitch leakages. In Figure *2-1* the placement of thermocouples 1-6 is shown with the steel plate that supports the tubes. The steel plate at the top was used to keep the tubes in the same position on the way down into the electrode.

The steel tubes for the thermocouples were placed as shown in Figure 2-1. Tubes 1, 4, 7 and 9 were placed 2 cm from the inside of the casing, and tubes 3, 6, 8, and 10 were placed at the tip of the fin in 36 cm from the casing. Position 2 and 5 are in-between position 1 and 3 (4 and 6) 17 cm away from the inside of the casing. Thermocouples 1-3 and 7-10 are placed about 2 cm away from the fin they are placed next to.

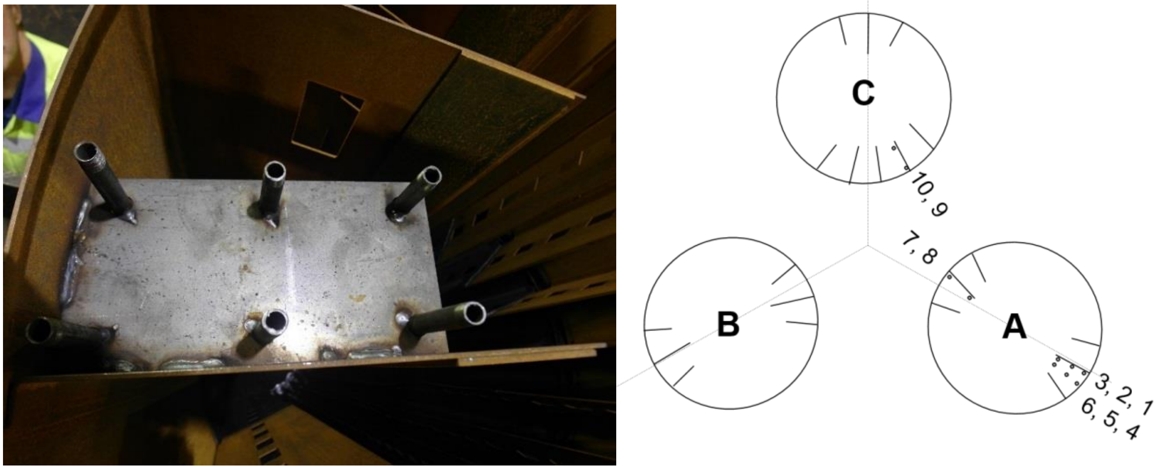

Figure 2-1: On the left - a picture of the tubes for thermocouples 1-6. On the right - the placement of thermocouples during the measurement. Only fins essential for the measurements are shown, but fins are placed around the whole casing.

Temperature profiles of the electrodes were measured by lowering thermocouples into the tubes mounted on the casing, and stopped at set intervals to measure temperature. The thermocouples were 18 m long K-type delivered by *TC ltd*. Measurements started approximately 4-8 meters above the top of the contact clamp. Thermocouples were also maintained in fixed positions over periods to log the temperature.

The length from the top of the casing to the top of the slipping ring was measured at the start of each measurement. The height from the top of the contact clamp to the uppermost slipping ring is constant and position of the thermocouples relative to the contact clamp can be calculated. Measurements can last for hours, and slipping was taken into account as the distance between top of casing to the uppermost slipping ring decreases when the electrode is slipped.

Figure 2-2 shows the measurement log as of 9th of April for thermocouples 1-3. For each movement of the thermocouples the time and height of the thermocouples were registered in the logbook. The average temperature for each step was used as the temperature for a given height. Measurements were stopped when the temperature reached approximately 1000° C or it was impossible to move the thermocouple further down.

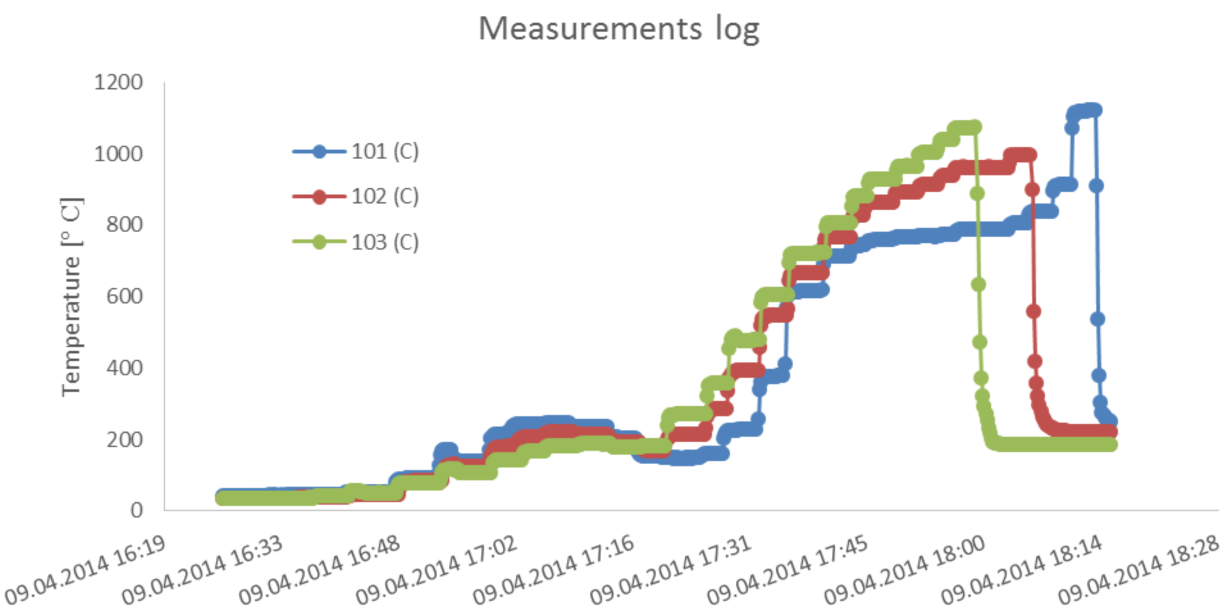

Figure 2-2: Log from data collector for TC1-3 during measurements on April 9; 101 corresponds to TC1, and 102 to TC2 etc.

3. RESULTS

Figure 3-1 shows the temperature interval from all measurements done with indication to where electrode paste and equipment is situated. The temperature rises to about 70-80°C as the melted paste level is reached. Further down the electrode the temperature will rise to a local maximum above the tip of the contact clamp. Inside the contact clamp temperature decreases as the paste is cooled by cooling water in the contact clamps, before it rises rapidly in the baking zone.

The electrode on the left in Figure 3-1 shows measurements taken 2 cm from the steel casing and the electrode on the right - 35 cm from the casing at the tip of the fins. The red vertical lines in the figure indicate these positions. Notable differences between the two figures are that the first temperature peak is smaller closer to the centre of the electrode (there is no temperature peak for the measurements positioned towards the furnace centre), and in the baking zone the temperatures rises quicker closer to the centre of the electrode.

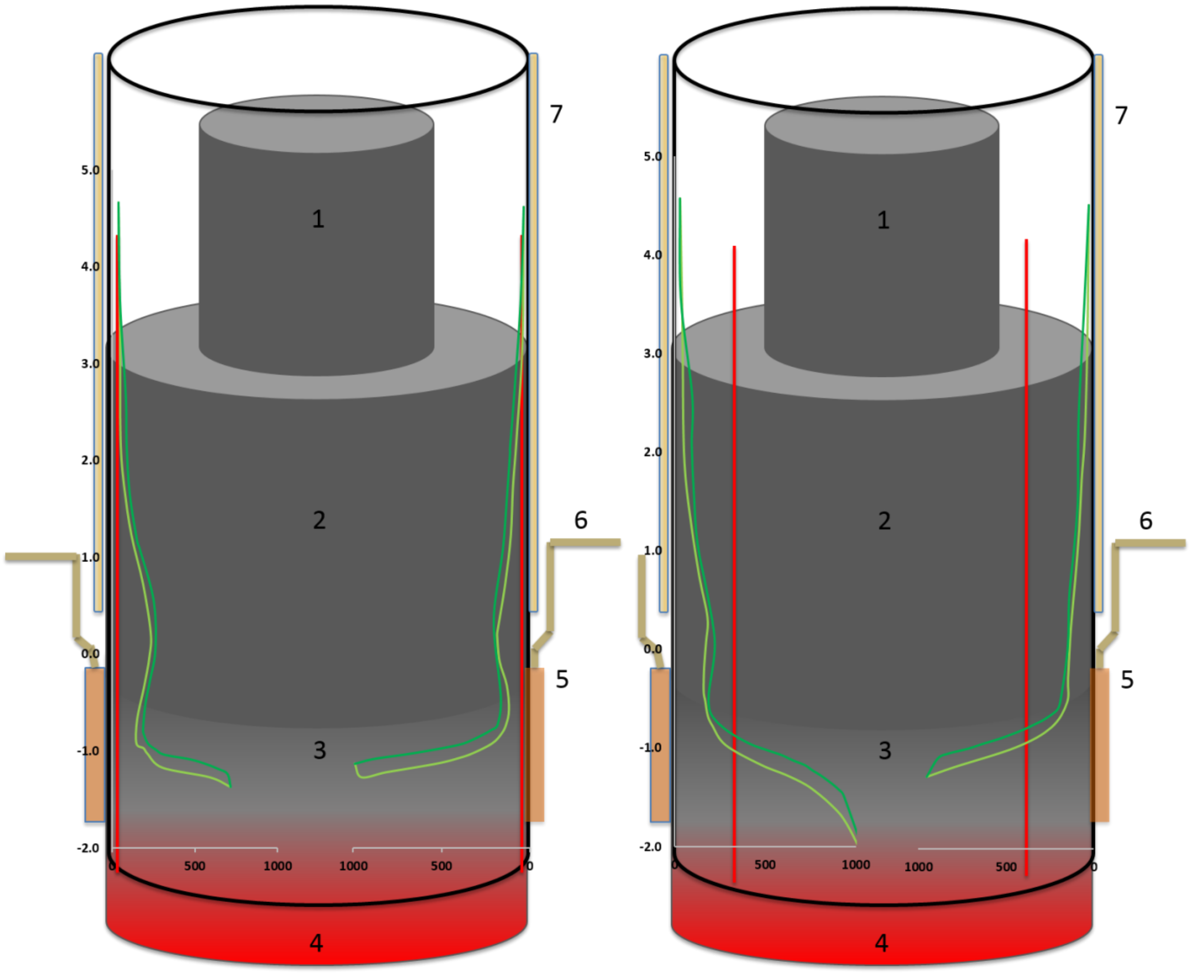

Figure 3-1: The temperature profiles from the measurements are shown in green as temperature bands. The red vertical line indicates where the measurements are taken, i.e. on the left hand side measurements are taken 2 cm from the casing and on the right - 35 cm from the casing. The measurements on the right in both figures are towards the furnace centre. The numbers shows the following: 1. Electrode paste cylinder 2. Melted electrode paste. 3. Baking zone of electrode paste. 4. Hot solid electrode. 5. Contact clamps. 6. Current tubes. 7. Heating air.

In Figure 3-2 temperatures are higher in positions 4-6 than the corresponding positions 1-3 in the area above the contact clamps. Within the contact clamp, the opposite is observed since temperatures are lower for positions 4-6 than positions 1-3. Thermocouples 1-3 are close to the fins, while thermocouples 4-6 are in between two fins. The difference in temperature is most evident for the comparison of position 1 vs 4 and the effect diminishes with the approximation of thermocouples to the centre of the electrode. As the difference between the positions almost diminishes at the tip of the fin, the penetration depth of these heat fluxes is limited.

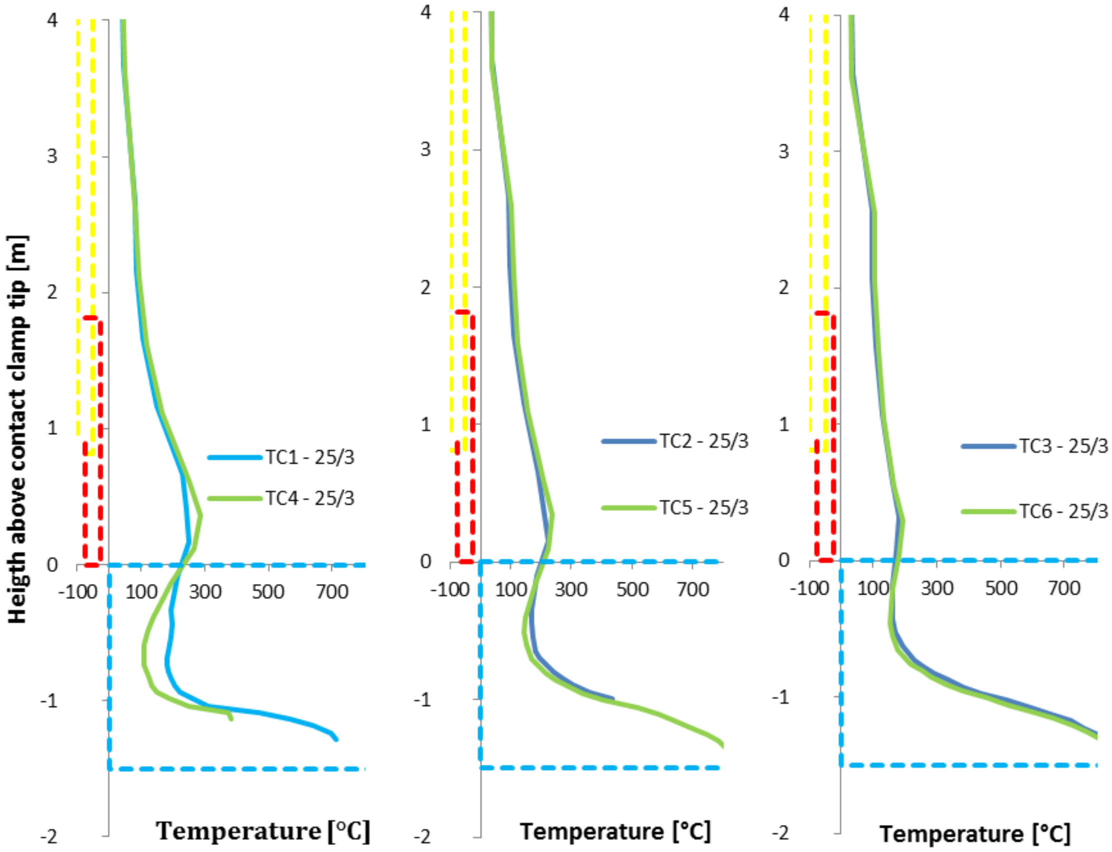

Figure 3-2: Comparison of temperature development in different positions on electrode A. Yellow dotted line depicts the position of the heating air. Red dotted line is the area where the bus tubes are close to the electrode. Blue dotted line show the contact clamps

Figure 3-3summarizes the temperature closest to the casing. The figure shows that the temperature in the area above the contact clamp is quite high due to induction from the current bars going to the contact clamps. This effect is best observed on thermocouples 1, 4, 7 and 9, i.e. the thermocouples closest to the casing. Figure 3-3 shows big variation in how high the temperature peak is between the different positions. TC1 and TC4 are quite close but different as discussed earlier, due to difference in distance to the fins. TC1 is hotter than TC7, which again is hotter than TC9 in the area 0.5 m above the contact clamp. This may be explained by differences in the position of the current bars, and differences in current in the current bar closest to the measurement position. However, these data are not known at present.

In the area 0.5 m above the contact clamp the temperature of TC4 in Figure 3-3 are close to 270°C, which is in the area that can lead to pitch distillation. TC1 peaks at approximately 230°C, and TC7 and TC9 are below 200°C in this area. The temperature peak in this area seems to be highest for the position in between the fins.

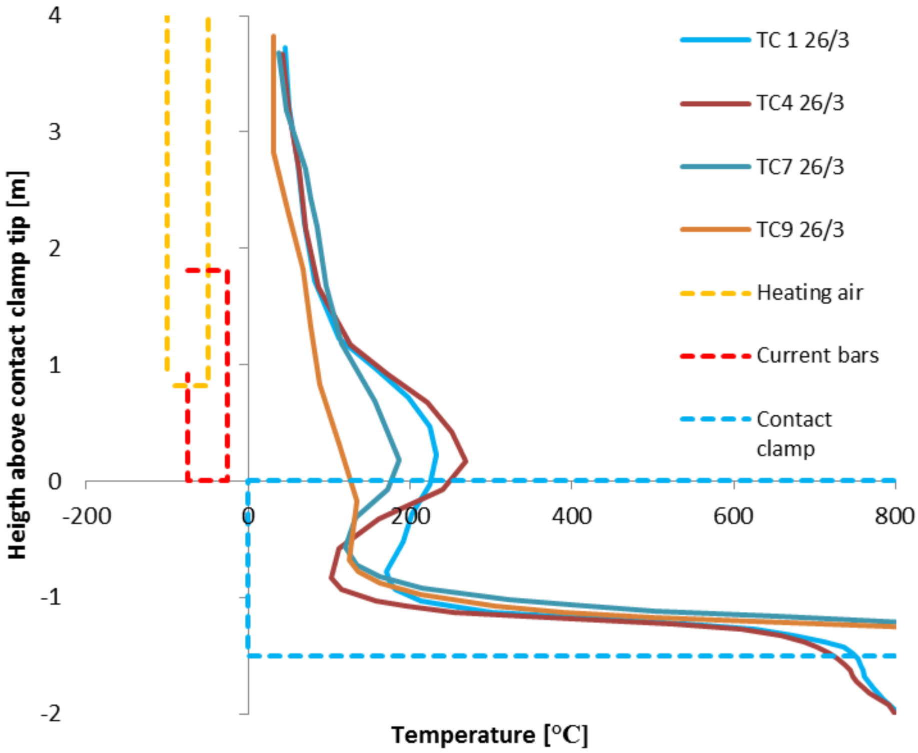

Figure 3-3: Temperature profiles from positions 1, 4, 7, and 9. The position of heated air flow, the position where current bars come into the electrode and the contact clamps are marked with dotted lines.

In Figure 3-4 the minimum and maximum temperature profiles are shown together with measurements before, during and after a furnace shutdown. For both TC1 and TC3 the effect of high slipping can be seen on the 2/4, when the line goes below the minimum for the temperature profiles. At first, the temperatures stay within the minimum/maximum borders but as the slipping increases the temperatures decreases.

The temperature profiles in Figure 3-4 from the furnace shutdown on April 3 were recorded around 10:00, approximately 3 hours before the shutdown. For TC1 the temperatures stay below the normal limits in the whole measurement range. However, closer to the centre of the electrode, i.e. TC3, the temperatures have not decreased as much. In the temperature trough 0.5 m below the contact clamp tip the temperature was within the range of profile measurements. The same can be seen approximately 0.8 m above the contact clamp.

During furnace start-up in Figure 3-4 temperatures recording has started approximately 17:00, 3 hours after furnace start-up, and were recorded until the next morning till 07:00. Close to the casing, the temperatures of TC1 during furnace start-up are tangent to the minimum temperature profile line in Figure 3-4. Closer to the electrode centre the temperatures does not rise as fast during start-up, but the distance between the minimum temperature profile and the start-up measurement is diminishing towards the end of the measurement.

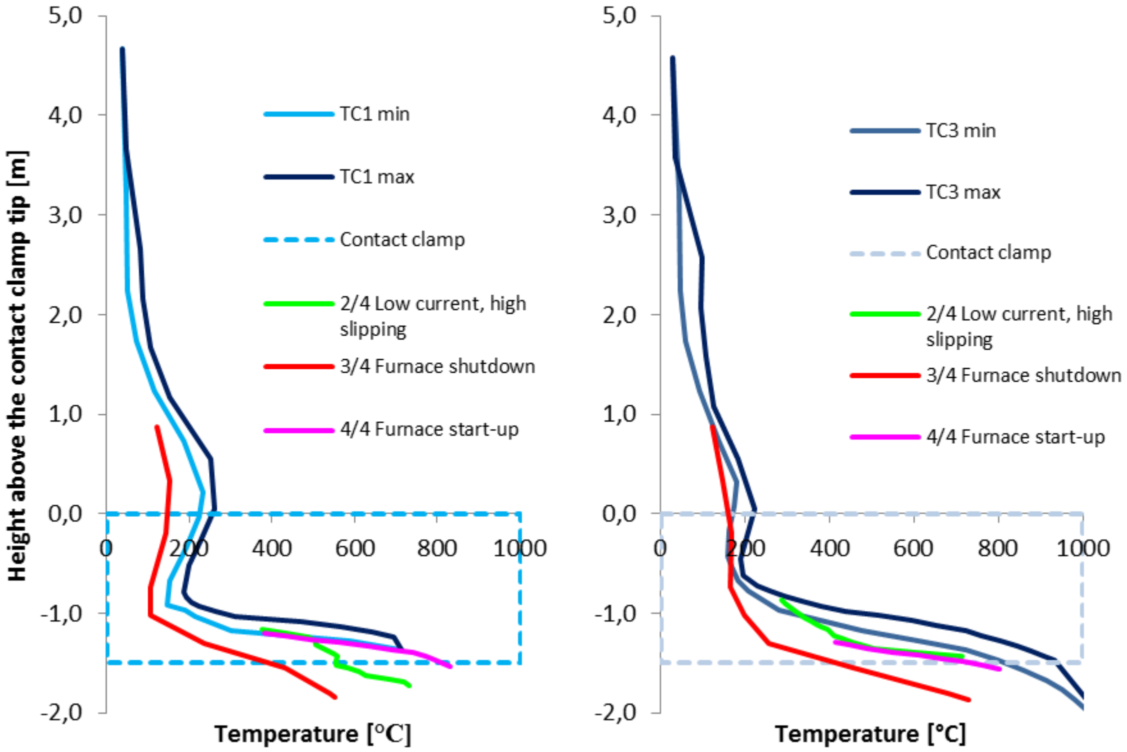

Figure 3-4: Minimum and maximum temperature profiles for thermocouple 1 and 3 with measurements taken overnight and during furnace shutdown.

COMSOL Multiphysics was used to model the heat transport in an electrode without fins and slipping of the electrode. The “conjugated heat transfer” mode was chosen to allow modelling the effect of the heating air. So far, only heat transport has been included in the model.

The model is axisymmetric, with carbon paste in the centre and casing outside the paste. To describe the thermal conductivity of the electrode paste a 4th degree polynomial function was adopted to thermal conductivity data given by I. McDougal et.al. [7]. For the other materials in the model, steel (Steel AISI 4340) and air, the material properties giv-en in COMSOL is used. The model uses a stationary solver with the temperature equation given as Equation 1.

$$\rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \qquad \mathbf{2}$$

Where **u** is the velocity field, T is the temperature, C_p is the heat capacity of the material, k is the thermal con-ductivity and Q is heat flux. However, for the electrode paste the velocity is assumed zero and the temperature equation for electrode paste becomes:

$$0 = \nabla \cdot (k \nabla T) + Q \qquad \mathbf{3}$$

Heat fluxes were chosen to get the best result for both the inductive heating and the cooling from cooling clamps. The boundary conditions of heat flux and temperatures are shown in *Figure 3-5*. The output of the model is given i nFigure *3-6* as a 3D plot of the temperature and a contour plot of temperature.

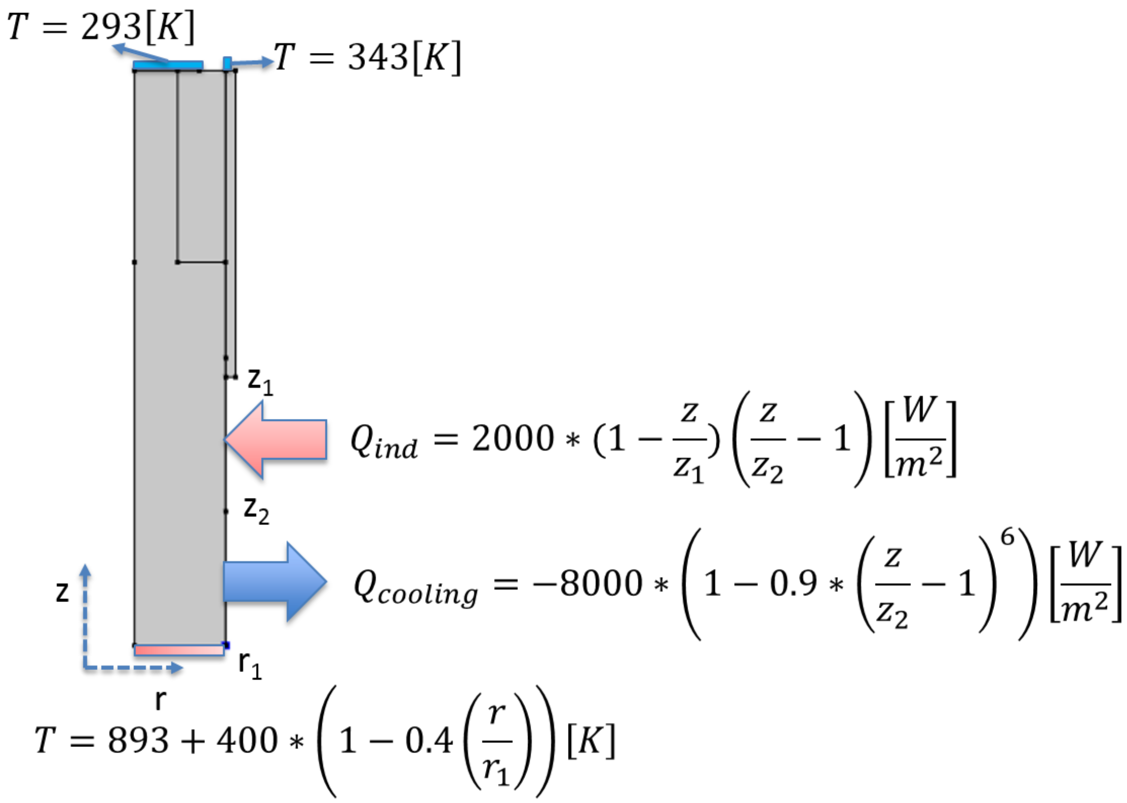

Figure 3-5: Heat flux and temperature input to the COMSOL model.

In Figure 3-6 a 2-D isothermal contour plot of temperatures up to 500 °C is shown to the left and a 3-D surface plot of temperatures up to 500 °C is shown to the right.

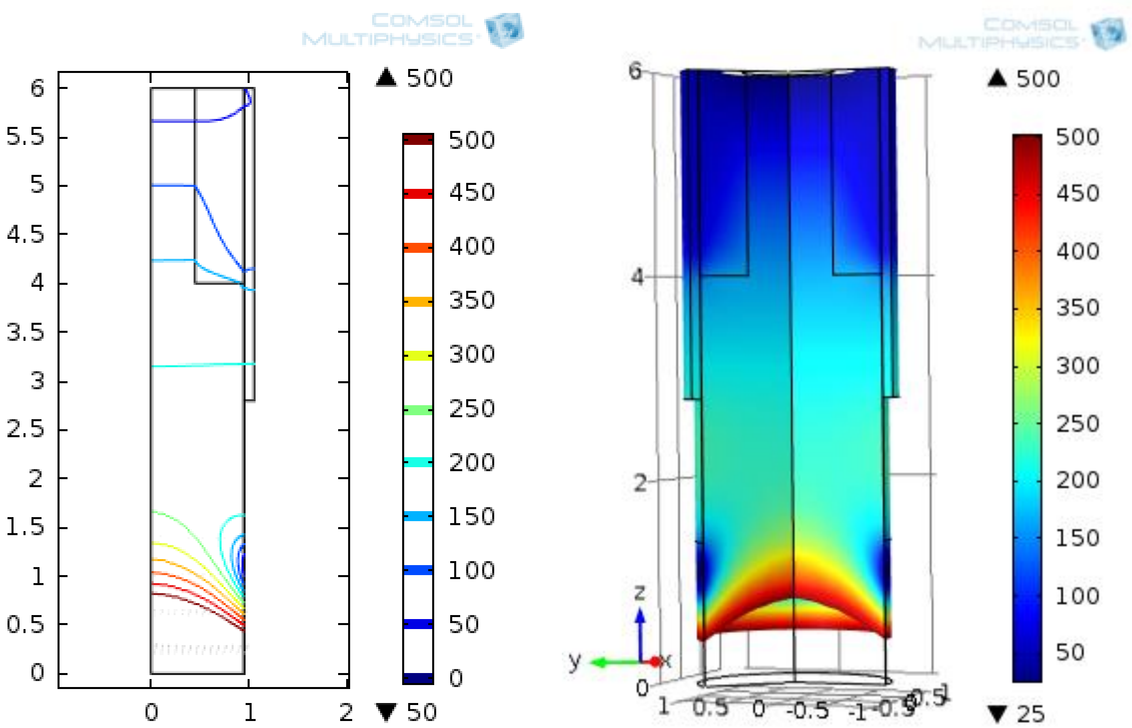

Figure 3-6: Output from COMSOL Multiphysics modelling. The temperatures are given in degrees Celsius.

4. DISCUSSION

The temperature bands of Figure *3-1* gives a good picture on how the temperature in a Søderberg electrode used in FeMn furnaces develops from electrode-paste cylinder addition to the baked electrode in the contact clamps. Further Figure *3-1* and Figure *3-2* show that effect of heating above the contact clamps and the cooling within the contact clamps decreases with approximation of measurements to the electrode centre done as expected when the source of heating/cooling comes from outside the electrode paste. Figure *3-2* also show that the measurement points in between fins are effected more of cooling/heating from the outside than the measurement positions close to the fins. The high heat conduction in the fin steel will decrease temperature gradients close to the fins by both radial and vertical heat transport.

In Figure *3-3* the temperature peak above the contact clamp tip is shown to vary between the different positions around the electrode. This peak is believed to come from induced currents from current bars going into the contact clamps. The effect of the induced current will vary depending on the distance from between casing and current bar and the current in the current bar. Thus, there are large differences in the temperature peak between the measurement positions. The highest measured temperature in this region is around 270°C and it is unlikely that this is the highest temperature in this area around the electrode. With temperatures above 270°C, there is a risk that light coal-tar pitch components will evaporate and rise in the electrode. If the lighter coal-tar pitch components condensate higher in the electrode the viscosity of the electrode paste will decrease and the risk of segregation will increase. To counteract the rise in temperature increased cooling by e.g. the "heating air" can be done. The heating air will in this region be colder than the casing/paste and therefore act as cooling. If the heating air cannot be used induction shield may be installed.

Increased slipping and reduced currents before electrode shutdowns are used to prevent breakages of the electrode caused by thermal shocks or thermal stresses [9]. Even with lower current and increased slipping, the baking isotherm (475 °C) stays within the current clamp for the measurements done, but as can be seen from the measurements electrode paste baking isotherm is lowered considerably in this period. The recovery time for temperatures in the lower parts of the contact clamps are considerably longer for measurement positions closer to the electrode centre than those close to the casing.

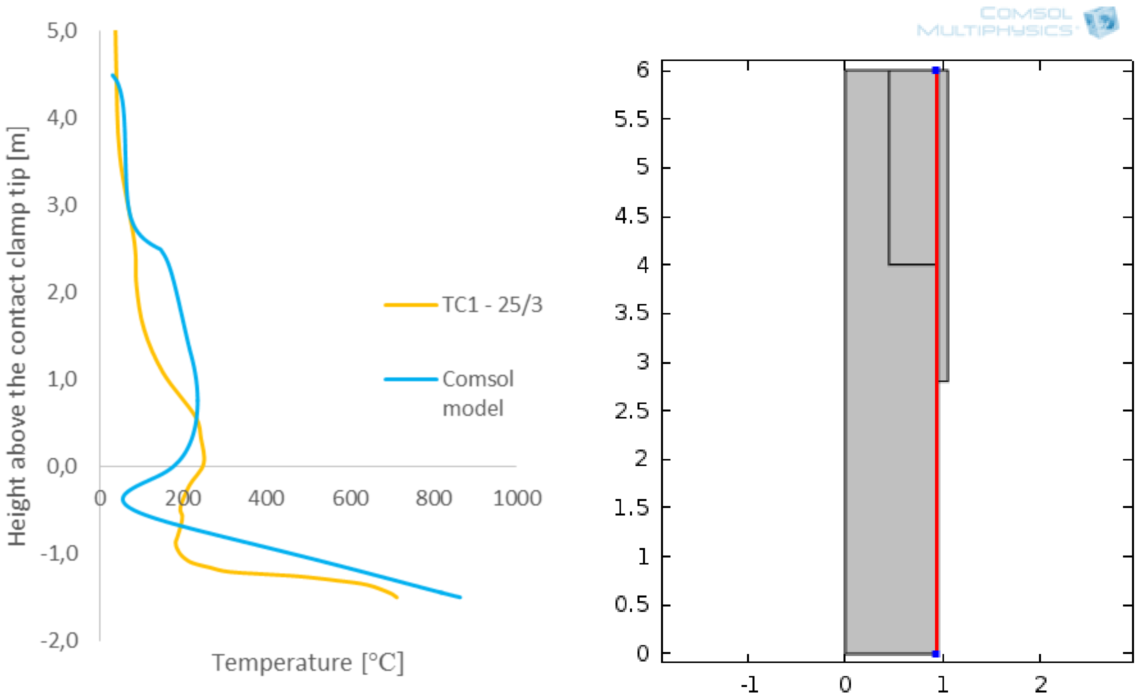

Figure 4-1: The temperature profile given by the COMSOL model is shown to the left and the position of the profile is given in the figure to the right, 2 cm from the casing

In Figure *4-1* the measured and COMSOL modelled temperature profile for the position 2 cm away from the casing is shown. The peak from positive heat flux above the contact clamp is shown approximately 0.5 m above the contact clamp tip. The through just below the contact clamp is almost at 50°C and one can also see where the model goes from paste to air with the sharp drop 2.5 m above the contact clamp. The through caused by the water-cooled clamps has a minimum which is lower in the contact clamp for the measured profile compared to the model. The temperature gradient is higher for the measured profile for the temperature rise 1 m above the clamp and 1 m below the clamp.

Figure 4-2 shows the temperature profile for measurements and calculated by the COMSOL model 35 cm into the electrode from the casing. The transition from air to paste at 2.5 m is seen where the temperature profile suddenly changes slope. The temperature profiles of the model and measurement are more similar with the approximation to the electrode centre where there are no fins to conduct heat.

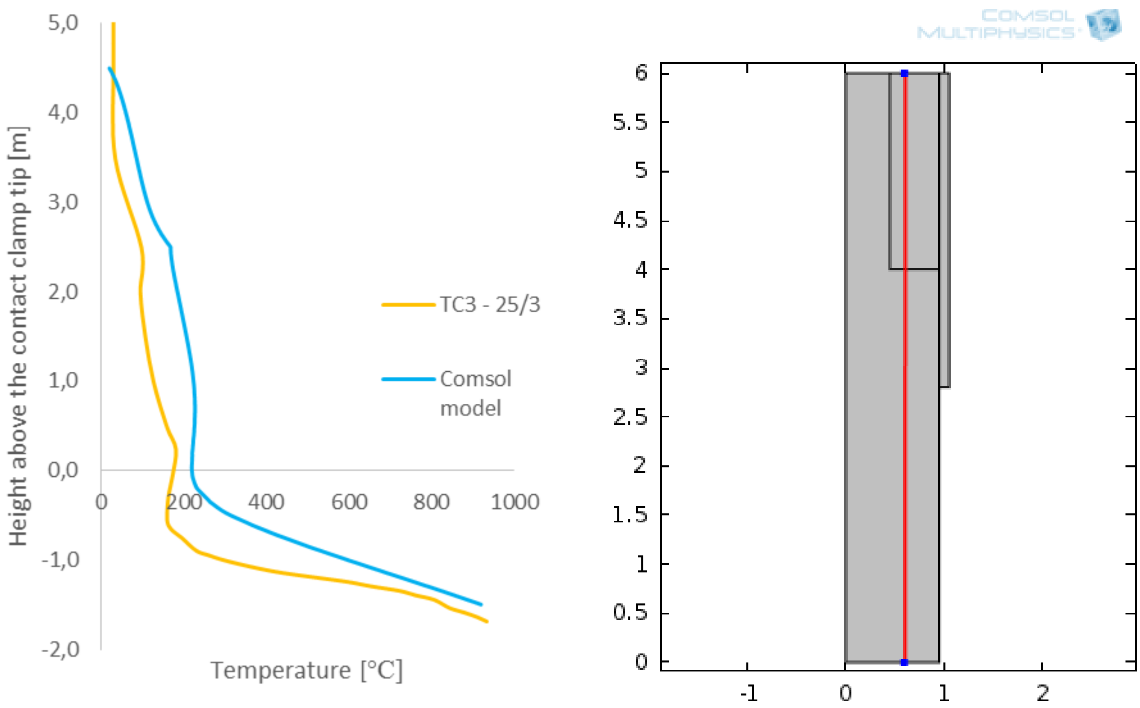

Figure 4-2: The temperature profile given by the model is shown to the left and the position of the profile is given in the figure to the right, 35 cm away from the casing

With many simplifications, a COMSOL model is able to reproduce the shape of temperature profiles quite accurately. It is clear that heat is added to the electrode paste above the contact clamps and removed within the clamps. The biggest discrepancy between measurements and model is probably due to the fact that the fins are not added to the model, which will reduce the heat conductivity. This can be seen as the temperature decreases slower for the modelled profile compared to the measured profile within the contact clamp and in the upper parts of the paste.

5. CONCLUSION

Temperature is more stable close to the fins than in-between fins, due to heat transport by the fins. Steel has higher heat conductivity than carbon paste and partly even out the effect of cooling from the contact clamp and heating by induction above the contact clamps.

Temperature increase close to the casing in the area above the contact clamp is probably caused by induction from current carrying copper bars. Temperatures can be as high as 270°C, which can lead to volatilization of light coal-tar pitch components. If light coal-tar pitch components re-condense within the electrode paste, and decrease paste viscosity problems with segregation can increase. The position of the bus tubes on the outside of the casing seems to be important for how high the temperature of the paste reaches in the area above the contact clamp.

Higher slipping rates before shutdown of furnace will lower the baking zone, but the baking zone is kept within the contact clamp for the shutdown procedure utilized in this case. During start-up of a FeMn furnace it is required that temperatures reach normal temperatures in more than 12 hours at the tip of the fins in the lower parts of the contact clamp. Whereas close to the casing temperatures are normal within 4 hours after start-up.

The form of the temperature profiles from a COMSOL model resembles the measured profiles, and the resemblance is better for thermocouples placed closer to the centre of the electrode. However, without the heat flux conducted by the fins a model of the temperature is inaccurate. A higher heat flux is needed to get the top of the electrode accurately modelled.

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