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Modelling paste flow and segregation in high performance Søderberg electrodes

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1. Introduction

Søderberg electrodes are used in the production of ferroalloys, silicon metals and calcium carbide

Background

The Søderberg electrode, depicted in Figure 1, is a continuously consumed electrode invented about 100 years ago by the company now known as Elkem. As the energy source in submerged arc furnaces, it conducts currents of up to 150kA to power the production of ferroalloys and calcium carbide.

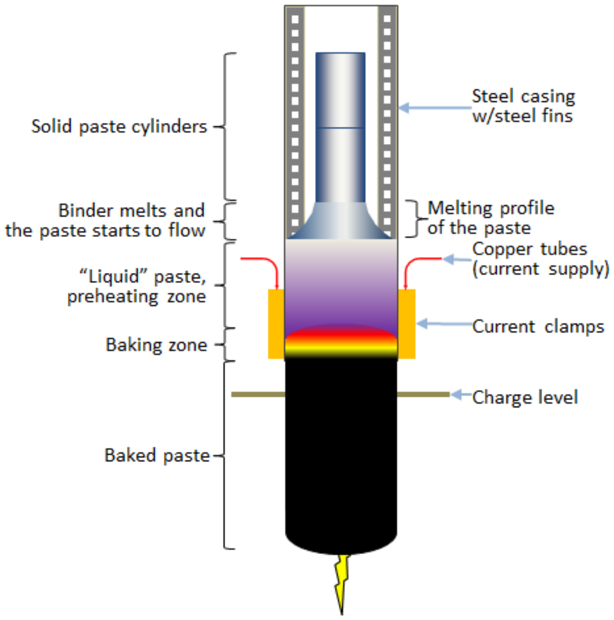

Figure 2: Diagram of the different parts of a Søderberg electrode, where paste cylinders are added at the top and go through the required melting and baking process.

The paste, a mixture of binder and calcined anthracite, is the raw material that makes the electrodes

Paste is used as the raw material to make the electrodes. It is a mixture of binder (tar and pitch) and calcined anthracite. It can be added at the top of the casing in the form of solid cylinders, as shown in Figure 1, as briquettes or as blocks. The casing is lowered at a constant speed called the slipping rate. The temperature increases in the electrode due to the heat induced by the current supplied to the current clamps, the heat supplied by the fans blowing hot air along the walls, as well as the heat from resistive heating in the baking zone and heat from the arcs at the tip of the electrode. The increasing temperature causes the paste cylinder to melt until it reaches the electrode casing, and then to bake as it reaches the current clamps. The melted paste flows due to a combination of the weight of the paste cylinders above and the motion of the casing.

The paste evolution as it is heated up is shown in Figure 1. As the paste is baked, it becomes highly conductive and allows the generation of electric arcs at the tip that power the smelting process. The correct melting and baking of paste is crucial in producing electrodes with the correct mechanical, thermal and electrical properties on which the entire production process depends on. Particularly, it is important that the paste cylinders melt slowly, creating the melting profile shown in Figure 1.

Segregation

When the paste melting is out of balance, segregation can occur. The process is illustrated in Figure 2. The causes of this phenomenon are not well understood, but it is known that the segregation problem began when changes in design led to a decrease in the space between the copper tubes, which conduct current to the clamps, and the electrode casing, resulting in unwanted electrical induction within the cylinder. The added heat due to induction causes an increase in temperature near the pre-heating zone, leading to a separation between the binder and the anthracite particles in the paste. The binder, which has a much lower viscosity than that of the paste, softens and moves up towards the region where the cylinders are beginning to melt. Consequently, a low viscosity *swamp* (the green region in Figure 2) is formed in the area where the cylinders are added, leaving the anthracite particles in the preheating zone, shown in purple. This eventually leads cylinders to sink down into the liquid paste, causing the resulting electrode to have sections with different material properties. In some situations, the segregated material can accumulate near the walls of the casing, altering the behaviour of the paste in those regions.

Segregation decreases the efficiency of the Søderberg electrode significantly, and can cause it to lose its anchoring to the casing. In some cases, the entire baked portion can fall off, enabling the liquid paste to flow freely into the furnace causing fires and often explosions. These kinds of breakages can cost the company up to £1m to rectify each time they happen.

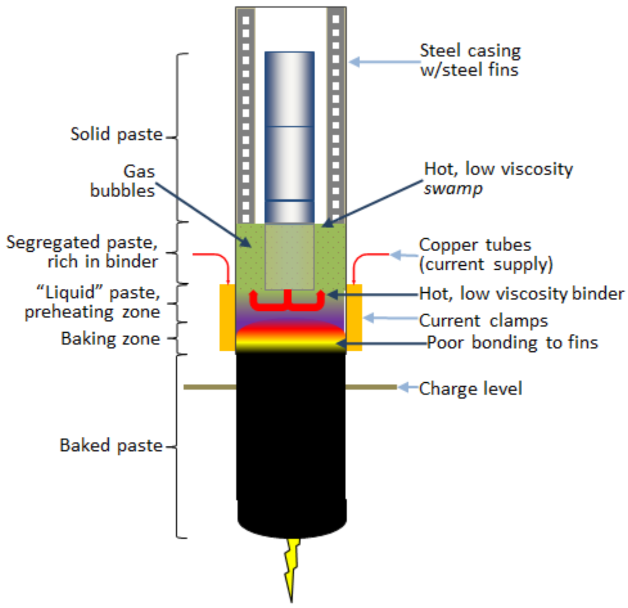

Figure 2: Schematic of paste segregation within a Søderberg electrode. The paste is heated up to a temperature so high that the binder separated from the solid aggregates, travels towards the top region and created a hot, low viscosity swamp into which the cylinders sink.

Elkem are interested in understanding the ideal operating conditions for the electrode so that the paste will have the correct melting profile shown in Figure 1, preventing the formation of the segregated region shown in Figure 2. Our aim is to make a mathematical model for the melting of the cylinders to see under which conditions they form a swamp.

Glossary of terms

- Péclet number: Ratio between the heat transferred due to the flow of the fluid (convection) and the heat conducted within the fluid.
- Compressive force: Application of force against an object that causes it to become squeezed, squashed or compacted.

A one dimensional mathematical model helps us to understand which parameters govern the general behaviour of the paste

2. Mathematical model

We focus our attention on the region at the centre of the electrode, disregarding the effects of segregated material sticking to the walls, for simplicity. We assume symmetry in the radial direction and so we will only consider variations in the direction of the axial coordinate x. Furthermore, we will split the domain into three regions:

- Region I comprises of the top part of the electrode, where the paste cylinders are added and begin to melt and extends down to the place where the paste reaches the casing (at some $x = \ell$). We assume that we know the initial velocity of the paste and the initial temperature.
- Region II begins when the electrode paste first reaches the casing, and corresponds to the melted region of the electrode. Baking begins to occur in this region, and we assume that the paste will move with the slipping rate.
- Region III begins where all the paste is baked, and will have the same constant velocity as Region II.

As an initial approach, we will assume that the system is in steady state and we write down a model which conserves mass, momentum and heat energy. The key variables are the radius of the paste cylinder, $R(x)$, the compressive load added at the top of the casing, $P(x)$ and the temperature distribution of the electrode, $T(x)$.

Comments

- Although the paste is comprised of two phases, binder and anthracite, we will consider it to behave as one phase, i.e. we assume that the binder and the anthracite are perfectly mixed and move at the same speed.
- The position where the paste first reaches the casing, the final temperature at the tip of the electrode, and the velocity of the paste flow inside the casing are all outputs of the model.
- The only heat source we will consider is the heat generated by the current supplied by the clamps, since this was found to be the dominant heat input to the system.
- The radius of the paste cylinder will change with the velocity of the paste, and will remain constant after it reaches the casing.
- For simplicity, we will assume that there is no radial variation in the model.

ℓ corresponds to where the paste first reaches the electrode casing, and is an output of the model

3. Results

We solve our simple mathematical model parametrised using experimental data describing the viscosity of the paste and the normal operating conditions of Søderberg electrodes. We analyse the model to determine the most important factors that affect the melting profile of the paste cylinders, as well as a temperature profile for the entire electrode.

Melting and temperature profile

The melting profile of the paste is governed by the relationship between the weight added at the top and the viscous strength of the paste

In Figure 3, we show the radius of the melted electrodes and the temperature as functions of position, with $x = 0$ m corresponding to the top of the electrode and $x = 7$ m corresponding to the area just below the clamps (as taken from data for a standard Søderberg electrode). Note that the paste is supplied at a temperature which allows it to flow, and reaches ℓ at around $x \approx 2.2$ m , which is above the area where the current is supplied. This is required for the correct functioning of the electrode system.

For the temperature profile, also shown in Figure 3, we see a constant temperature until it reaches the area of the current clamps. Here, the applied electrical current causes a sudden increase in temperature, which rises to almost 1000°C. This corresponds well with Elkem's experimental data. However, we see that temperature decreases after it passes the area of the clamps. This is due to our simplifying assumption that the electrode tip does not add heat to the system, and is not observed in a real situation.

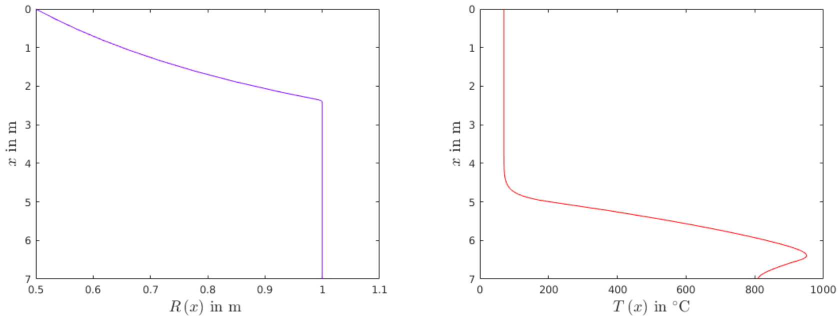

Figure 3: (left) Graph showing the radius of the melting paste cylinder which varies with position. The cylinder have an initial radius of 0.5 m and the casing has a radius of 1 m. Once the paste reaches the casing, the radius remains constant. (right) Temperature (in °C) for a Søderberg electrode where the only heat source is due to the applied current at the current clamps (located at $5 < x < 6.5$ m).

Compressive force vs strength of the paste

The parameter β relates the applied load with the viscous forces of the electrode

When analysing the model, the key dimensionless parameter was found to be β, which relates the compressive force applied to the electrode due to the paste cylinders added on top to the viscous forces that determine the strength of the paste throughout the electrode. Varying β results in changes to the melting profile, as seen in Figure 4. We see that the higher the value of β, the shorter the transition zone over which the paste reaches the outer casing.

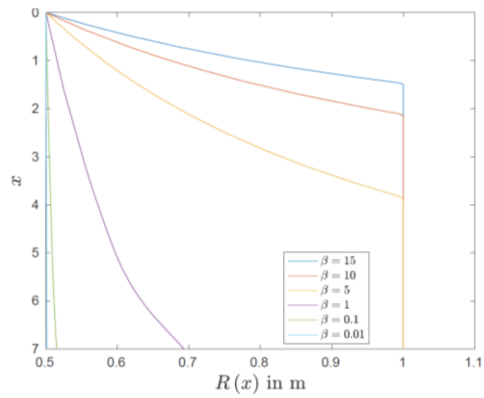

Figure 4: Graph showing how the radius of the melting paste cylinder varies with position for different values of β.

For β smaller than 5, the paste does not reach the casing at all, which in practice means that there is an operation problem in the electrode which can compromise the entire process. Using typical operating parameters, $\beta \approx 8.8$, our numerical solutions show that there should be no operational issues in this case.

Péclet number

Using typical operating parameters, we calculate that the Péclet number, which is the ratio between convective and conductive heat transport, is about 38, indicating that the heat transferred due to the paste velocity is more important than the heat conducted through the electrode, and indicates that some further simplifying assumptions can be made by neglecting the conduction term in our temperature equation.

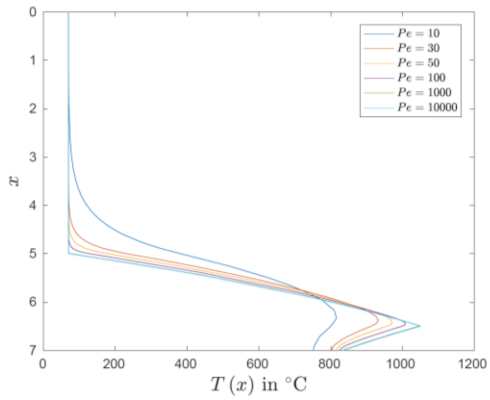

Figure 5: Numerical results of the temperature profile of a Søderberg electrode of the Péclet number.

Taking Pe to be very large provides with reasonable results, which allow further simplifications

We show the temperature profile in Figure 5 for various values of the Péclet number. We see that, as the Péclet number increases, the profile becomes sharper. When $Pe = 10$, for example, the temperature starts increasing at around 3 m. As we increase Pe, the temperature will begin to change further down in the electrode, and when we get to a very large value, in this case $Pe = 10000$, this transition becomes very sharp. This indicates that we can make further simplifications to the model by taking an infinitely large Péclet number and still obtain the correct behaviour.

4. Discussion, Conclusions & Recommendations

We have derived a 1-D mathematical model to describe the paste melting process inside a Søderberg electrode. Our initial numerical simulations show good agreement with Elkem's experimental results. However, the assumptions regarding the viscosity model must be revisited, as well as the heat balance in the temperature equation.

We found that the melting profile is governed by the relationship between the weight of the paste cylinders added at the top and the strength of the paste due to viscous forces. If the weight at the top is insufficient, the electrode paste will never reach the casing, leading to problems within the electrode, which may include segregation, breakage and explosions.

There are several key ways in which the model could be improved:

- We could include the heat generated at the tip of the electrode.
- As a middle step towards a full segregation model, a segregated phase could be incorporated, which will have a different (temperature-dependent) viscosity to the paste Our aim is to use this extended model to determine the position of the lower viscosity swamp.
- The viscosity model for the paste must be refined in order to better represent experimental data. Experiments that determine how the properties of the paste vary with temperature and applied stress would be very useful in order to ensure that the model accurately incorporates the real paste properties.
- The paste could be considered as a two phase flow. In this set up, the binder and the anthracite particles will have different velocities, and segregation will occur when the binder separates from the solid particles. Our aim is to use this two phase model to examine the evolution of the segregated region.

- Finally, the model could be extended into 2 dimensions. This will provide a better understanding of how the temperature varies radially, as well as vertically, which will allow a better estimate of the position of the melting and baking zone in the electrode.

5. Potential Impact

The current methods used by Elkem to identify, prevent and contain segregation problems in Søderberg electrodes are mostly empirical and based on experience. They are not standardised and they are used intuitively. Furthermore, the temperature in the melting and baking zone is so high that it is not possible to install thermocouples or other devices to monitor the temperature and use real time data to prevent conditions that may lead to segregation. Therefore, a better understanding of segretation, as well as the operational parameters that affect it, will allow more efficient prevention and counter-active measures to be applied. This will aid in keeping the electrodes working under ideal operation conditions.

Rolf Birkeland, Elkem Technology, commented *"We in Elkem think that Alissa has done a very good job during her mini-project. Segregation problems in Søderberg electrodes have haunted an entire industry for a century. The development of a mathematical model that can predict the paste flow pattern and predict the start of segregation in Søderberg electrodes has not been done before. The implementation of such a model in the furnace's process control system will surely give Elkem a competitive edge over the rest of the industry. The potential impact for Elkem of such a monitoring system with respect to cost saving and operational stability is large."*