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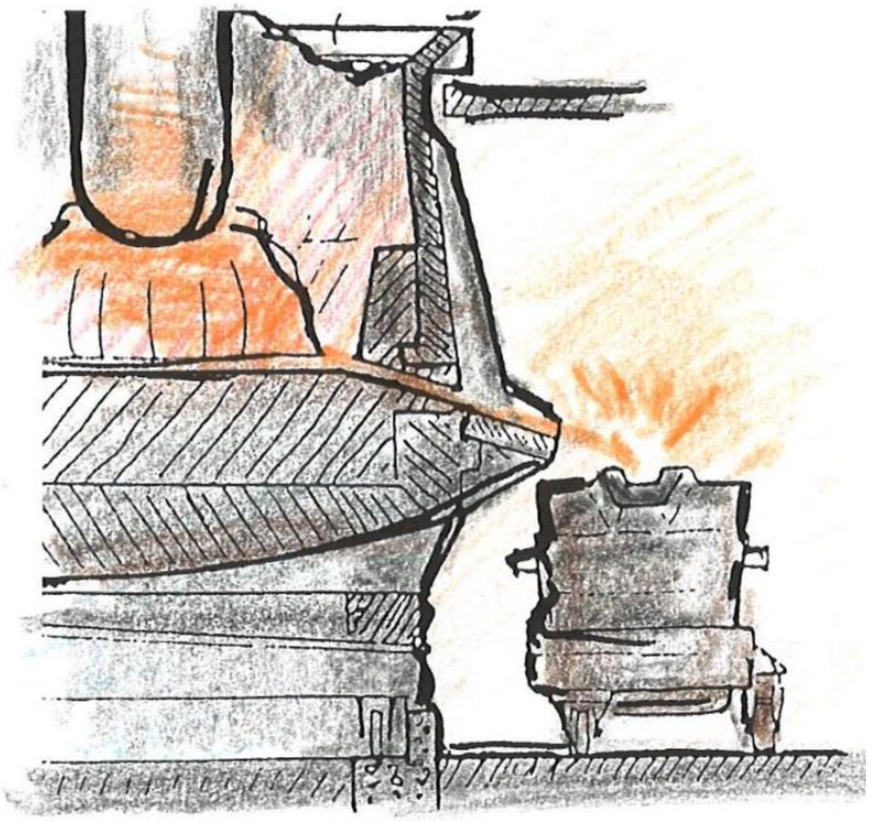

Clogging Mechanisms in Silicon Tapping

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Contents

1 Introduction

Background

Elkem is one of the world's leading producers of silicon and silicon alloys. The core of silicon production plants are arc furnaces (a cross section of one is shown in figure 1), where silicon is extracted from quartz rock. The quartz rock is fed in at the top of the furnace along with carbon materials such as woodchips, and heat from electrodes in the furnace allows a chemical reaction to take place, which releases the silicon from the quartz, creating several gases in the process. These reactions take place at the top of a crater: large cavities below the electrodes filled with gases. Once the silicon is formed it drops down to form a pool of liquid below the crater.

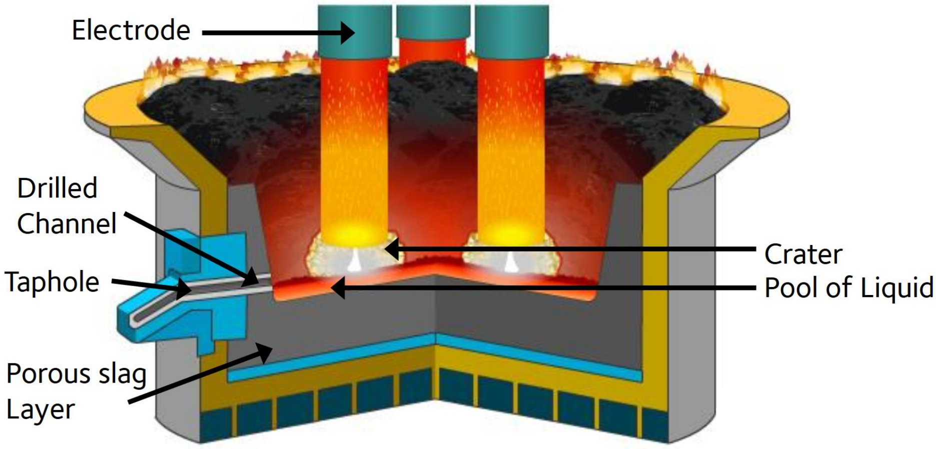

Figure 1 – A cross section of an arc furnace.

To extract the silicon from the furnace it must flow through a porous layer of solid slag.

As well as producing silicon, impurities in the quartz cause many other solid and liquid waste products to be produced within the furnace. The waste product is called *slag*. Some slag is extracted from the furnace along with the silicon, while other slag solidifies and forms a porous layer around the walls of the furnace. Slag has a wide variety of densities, viscosities, and melting points, and the porous layer they form can vary in structure in different parts of the furnace. The two samples of solidified slag shown in figure 4 come from different parts of the same furnace after it was shut down for a renovation project. The slag on the left has very few holes through it and it looks like the silicon would flow between the large "bricks". On the other hand the slag on the right is more porous, with holes allowing liquid to flow through rather than round it.

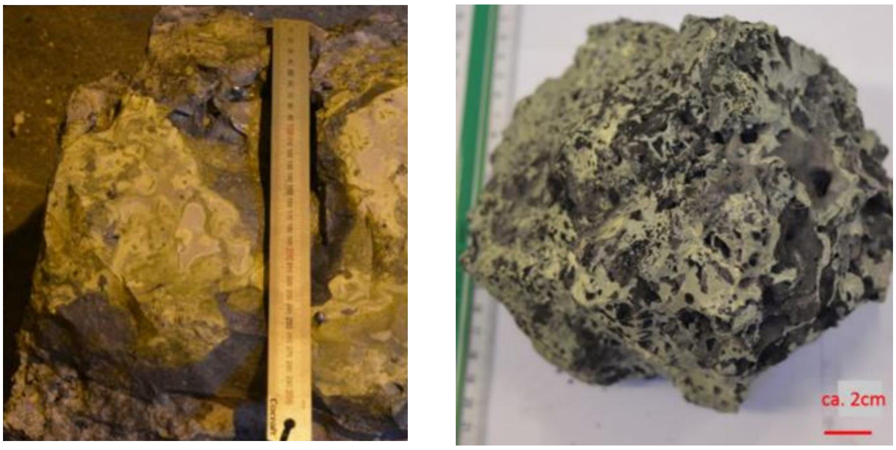

Figure 2 – Two samples of slag from a furnace excavation, pictures reproduced with permission from [1].

Tapping

The process of extracting the liquid silicon through the furnace is called *tapping*, where a *taphole* is opened in the side of the furnace to allow the liquid to drain out. When a new taphole is opened an attempt is made to bore a channel through the porous layer using heavy mechanical equipment or a graphite electrode to melt the slag. In the ideal situation, shown in Figure 3, the channel will go all the way through the porous layer but this is not always the case. Sometimes the channel only goes part of the way through the porous layer, slowing the flow rate of silicon out. Furthermore the depth of liquid in the furnace is sometimes misjudged and the taphole opens up above the liquid. Gases in the furnace can then flow out through the taphole, increasing the pollution caused by the industrial process and creating dangerous working conditions for the furnace operators.

High viscosity slags can clog the porous layer, reducing the flow of silicon.

Normally the flow rate out of a taphole will decrease after some time. This is because the channel becomes clogged, either because the slag is so viscous that the pressure drop cannot push it through the porous layer or the pores become blocked by solid slag particles. The clogging requires the channel through the porous layer to be re-drilled, which is a costly procedure since it can introduce contaminants into the liquid silicon, decreasing the quality of the product.

Our aim is to create a mathematical model that describes how the slag layer clogs the taphole, in order to provide insight to Elkem about how the parameters affect the process.

Glossary of terms

- **Porosity:** The fraction of empty space within a material through which a liquid can flow.
- **Tapping:** The process of removing liquid metal from a furnace.
- **Slag:** The solid and liquid waste products from the reactions occuring the furnace.
- **Porous Layer:** The porous layer of slag that builds up around the furnace walls.
- **Drilling:** The process of boring a channel through the porous layer, allowing liquid to flow out the furnace.

2 Mathematical model

We focus on the flow of liquid in the small part of the furnace around the entrance to the taphole, as shown in figure 3. We choose this part of the furnace since it includes the pool of liquid, the porous slag layer, and the start of the taphole. We aim to use the model to give a better understanding about how the flow transitions between these regions. To keep our model simple, we treat the geometry like a pipe; with an inlet, an outlet and solid walls connecting them. This avoids the complicated mathematical problem of tracking where the surface of the fluid is.

Fluid Flow

We will model the transition of the fluid through the porous layer and its exit.

Our model will describe the flow of a single fluid whose viscosity changes with the amount of liquid slag it contains. This means that the liquid slag and silicon will never separate into two distinct layers and instead will always be mixed together. It is well known by the furnace operators that the viscosity of both silicon and slag varies with temperature, as shown in figure 4a. The effective viscosity of the mixture is calculated by taking the harmonic mean of the two liquids, weighted by the amount of volume taken up by each liquid. The variation of the viscosity with the percentage of liquid slag at temperatures of 1800 K and 2000 K is shown in figure 4b. We see that the viscosity changes slowly with the amount of slag in the liquid until the percentage gets very high. As we also see, the change in viscosity due to altering the temperature is much smaller than that due to compositional changes. In our model we will also assume that:

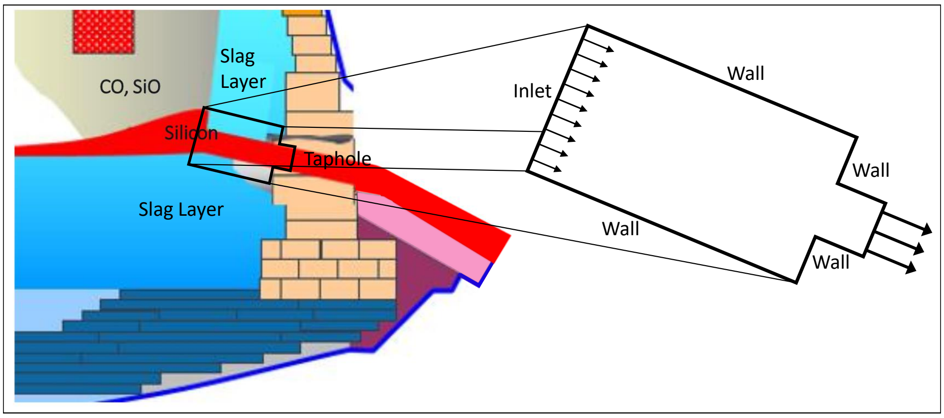

Figure 3 – A cross section of the taphole and the part of the furnace under consideration.

- The depth of liquid is deep enough that no gas enters this region of the furnace.
- A constant overpressure in the crater, caused by creation of gas, drives the flow towards the taphole.
- The density of the liquid silicon and liquid slag is the same.
- The slag is made up of 98% Silica, 1% Aluminium Oxide, and 1% Calcium Oxide.
- There is no solidification of either the silicon or the slag.
- The incoming fluid contains 15% liquid slag.
- The flow is two-dimensional.

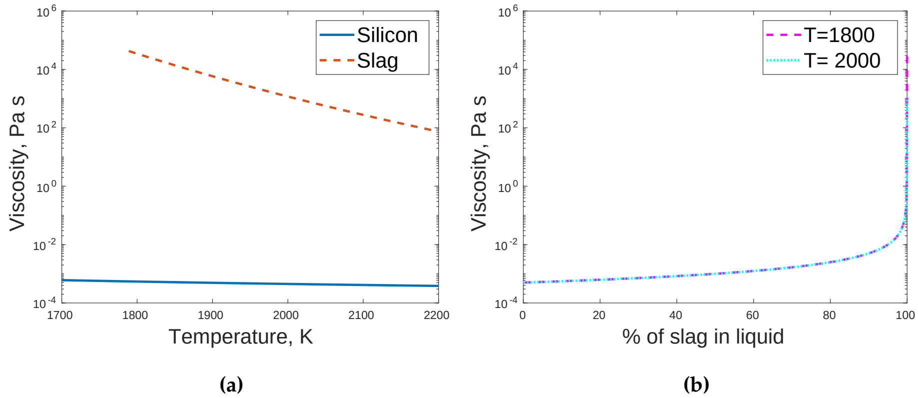

Figure 4 – Graph showing how (a) the viscosities of pure silicon and pure slag varies with temperature, and (b) the viscosity of a mixture changes with the amount of slag.

In our model, the silicon is a single fluid whose viscosity changes with concentration of liquid slag.

We derive the governing equations by considering conservation of mass and momentum of the fluid, and conservation of the amount of liquid slag. Together they form a system of coupled partial differential equations for the fluid velocity and pressure and the slag concentration. In the model there are two physical mechanisms that can change the concentration of slag; *advection* and *diffusion*. Advection is when small particles in a fluid are carried along by the fluid. Diffusion, on the other hand, is the tendency of particles to move from areas of high concentration to areas of low concentration.

Clogging

If the viscosity of the fluid becomes higher at some location in the furnace, the resistance of the fluid to the flow will increase, which will have an effect on the surounding fluid. This causes the overall flow rate through the taphole to reduce, simulating clogging. The only way viscosity can vary in our model is through the concentration of liquid slag. Since initially all the fluid entering the pipe contains the same amount of slag, and all the fluid flows out of the taphole, advection will remove slag from the pipe, so cannot be the cause of clogging. On the other hand diffusion allows the slag to enter parts of the domain where the fluid is not flowing very fast and build up there, so this could cause the clogging effect. Unfortunately there are no measurements of D, the diffusivity of liquid slag in liquid silicon, but if we assume the droplets to be perfect spheres, then we can use a formula derived by Einstein [2] to find that $D \approx 2.0 \times 10^{-3}\,\mathrm{m}^2\,\mathrm{s}^{-1}$, which is a very small diffusion constant. Using appropriate paramters for the tapping flow, we find that advection dominates the behaviour of the slag except possibly in the boundary layers near the walls of the channel.

3 Results

The amount of slag reaches a steady state but no clogging occurs so high viscosity slag cannot be the cause of the clogging.

We solve the mathematical model to generate simulations of the flow near the entrance to the taphole. We assume that the silicon enters the domain through the inlet at the left and contains a prescribed amount of slag. We run the simulation until we reach a steady state where neither the velocity of the silicon nor the concentration of the slag changes over time. The resulting steady-state velocity field can be seen in Figure 5. The colour indicates the magnitude of the velocity with red high and blue low, and the streamlines show the direction the fluid is flowing. We see that there are dark blue regions extending out from the top and bottom righthand corners. These are areas of very low velocity where we expect the slag to build up causing clogging. The concentration of slag is plotted in Figure 6 where red is high concentration of slag and blue is low concentration of slag. The black arrows on the main diagram show where the two vertical slices of the amount of slag are taken and plotted below. We see that, in the middle of the domain, the amount of slag is uniform across the domain. Just before the taphole, we see that there is a small increase in the concentration of slag near the walls when compared to the concentration at the centre of the slice, which would give a correspondingly higher viscosity at those locations. We note that we have presented the steady state velocity and concentration, and thus we do not see the feedback loop we hypothesised between the velocity, concentration, and viscosity. Our model therefore gives no evidence to support the hypothesis that clogging is caused by an increase in viscosity causing the pressure gradient to be insufficient to drive the flow.

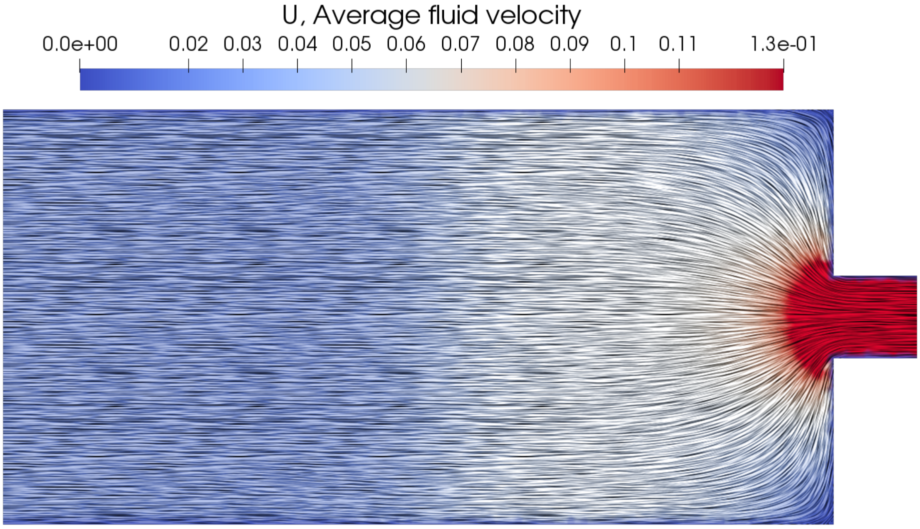

Figure 5 – The average fluid velocity at $t = 10.0\,\mathrm{s}$ **when** $D = 2.0 \times 10^{-3}\,\mathrm{m}^2\,\mathrm{s}^{-1}$**.**

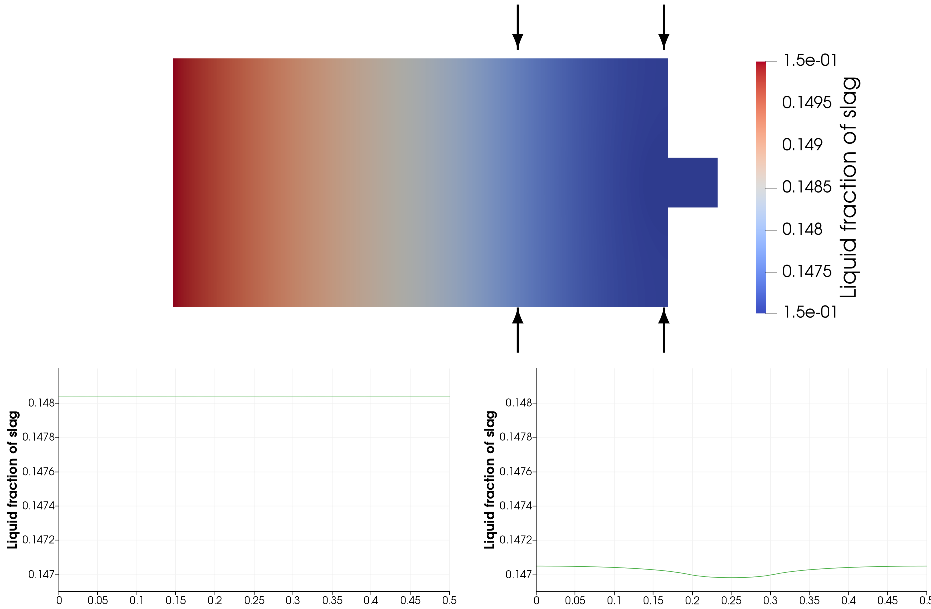

Figure 6 – The amount of liquid slag $t = 10.0\,\mathrm{s}$ in the domain when $D = 2.0 \times 10^{-3}\,\mathrm{m^2\,s^{-1}}$, driven by a pressure difference of $1.0\,\mathrm{kPa}$. The black lines show where the two vertical slices have been taken.

4 Discussion, conclusions, & recommendations

We built a model that describes the flow of liquid within the furnacein which we treat the silicon as a fluid and the slag as a dissolved species. Our model comprises a balance of mass and momentum of the silicon flowing in the furnace along with conservation of the amount of slag. These are coupled through the viscosity of silicon varying with the concentraiton of slag. We solved the model numerically using a finite element scheme. By varying the ratio of advection to diffusion, we have been able to show that our model can demonstrate the build up of liquid slag which could result in clogging like that seen in the furnace.

Although the results show our model can predict clogging, there are various additions to the physics that we should incorporate to get more realistic results, for example:

- The solidification rate of the slag, since the temperature at the furnace wall can be below the melting point of the slag. This would mean tracking the temperature in the furnace, so its effect on viscosity could also be incorporated.
- The density of the slag should be greater than that of silicon, and gravity may then cause the separation of the slag from the silicon.
- The effect of the drill hole should be captured by allowing the porosity to vary vertically as well as horizontally.
- The flow of the gas should be considered and how it affects the flow of the liquid.
- The limit of the model in which the silicon velocity is in quasi-steady state and only the amount of solid slag changes with time should be considered. This would allow us to capture the behaviour of the model on a longer timescale.

We should also look at using more specialised numerical schemes that are better suited to solving advection problems with a small amount of diffusion: either because they take information "upwind" of each point, or because they use a scheme that strongly conserves quantities in the model.

5 Potential impact

Our work provides a preliminary model of the behaviour of the fluid around the taphole. We have used the model to show that very viscous liquid slag is unlikely to be the dominant effect in the clogging of the taphole and suggests that further research should be focused more towards solidification mechanisms.

Dr Aasgeir Valderhaug, the R&D Director at Elkem, said: "*Clogging in the tap hole is a major obstacle to maintain stable production of silicon from a furnace, and the processes causing this clogging are not well understand. In particular, we want to know how slag affects the silicon flow out of the furnace. Matthew's work has been helpful in describing the complex coupled physical effects and he has developed a model that will be used to increase our understanding of these conditions. Matthew has communicated his work and results in a very clear way to the scientists and engineers in Elkem.*"

References

[1] M.Tangstad M.Ksiazek and E. Ringdalen. The rapid si-furnace excavation - an unique chance to investigate the interior of the furnace. Infacon XV: International Ferro-Alloys Congress, 2018.

[2] Christina Cruickshank Miller. The stokes-einstein law for diffusion in solution. *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, 106(740): 724–749, 1924.