InFoMM
Industrially Focused Mathematical Modelling

UNIVERSITY OF OXFORD

Clogging of Charge in Silicon Furnaces

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Processing silicon in an industrial furnace includes a series of chemical reactions. Quartz and some form of carbon (typically a mixture of charcoal, coal, woodchips, and coke), collectively called the *charge*, are added to the furnace through the top. Elkem use a process where three electrodes pass a high current through the charge, melting the raw materials. The melting of the charge creates a cavity, called the crater, in the lower part of the furnace. The quartz and carbon undergo multiple chemical reactions, some of which yield liquid silicon, which is tapped off on the side of the furnace. Other reactions create gaseous silicon monoxide (SiO) and carbon monoxide (CO) which are vented out of the crater through channels in the charge. The SiO condenses on the surface of the charge as it cools (Figure 1). The condensate continues to grow on the surface of the channels in the charge and eventually clogs and blocks the channels. Blockages cause the pressure in the crater to increase excessively. To mitigate this, the charge is *stoked* approximately hourly. Stoking is the process of breaking up and redistributing the charge, creating new channels. Our aim is to understand the processes that contribute to the build up of the condensate to help optimize Elkem's silicon process.

Mathematical Model

We develop a mathematical model for the growth of the condensate in idealized rectangular channels. We derive expressions for the temperature in the gas and condensate, the concentration of SiO and CO, the fluid flow of the gas through the channel, and finally, conservation equations on the gas-condensate interface. We reduce the complexity of the model using the relative sizes of the parameters for guidance. Despite the reduction, the reduced model is still difficult to solve—even numerically. Therefore, we make further assumptions about the behaviour of the gas pressure, the temperature profile in the charge, and the speed at which the condensation reaction proceeds. We solve the simplified model numerically.

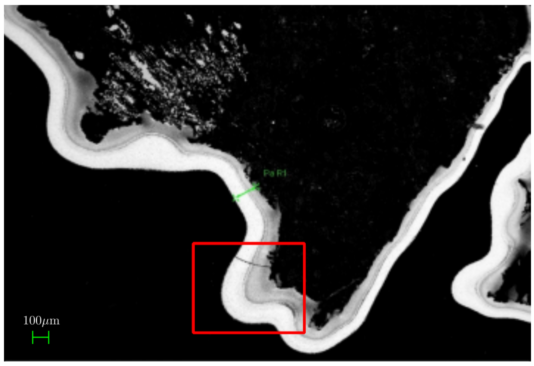

Figure 1—Electron microscope image of the condensate. The dark upper region is a particle of charge, and the white layer is the condensate.

Results

In Figure 2, we show the numerical solution for the concentration of SiO in a long and thin channel for nominal furnace values, in the case where we consider a channel of width 3mm and length of 3m that is initially devoid of gas. The gas enters from the bottom and is vented upward. We observe that the condensate grows in a narrow region as the gas starts to cool. This causes a pronounced peak, which consumes the majority of the SiO in the gas. As there is less SiO available in the upper region of the channel, the condensate growth is greatly reduced. We see that the concentration of SiO is almost uniform across the width of the channel. For a channel of this size, the movement of the SiO is dominated by the natural tendency to diffuse across the width of the channel, and not by the flow of the gas carrying it up the channel, although we find that this is not always the case for all channel widths. The skewed peak shape of the condensate is reminiscent of what is observed in small scale experiments in the laboratory. However, in these experiments, the decrease of the condensate in the upper region of the channel is more pronounced—showing condensation is restricted to the lower region of the channel.

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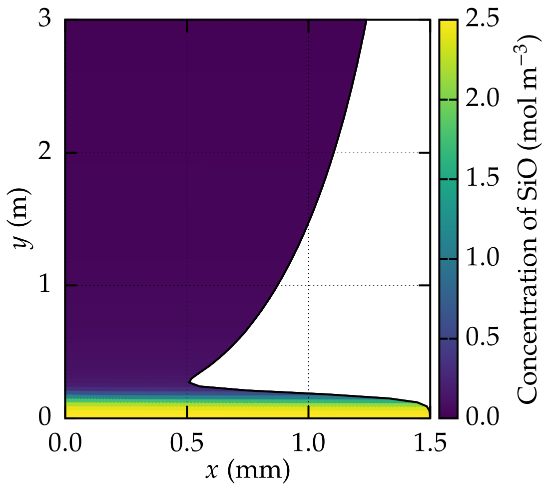

Figure 2—Concentration of SiO in a long, thin channel after two hours. The white region depicts the condensate layer. Only half of the channel is shown because of symmetry.

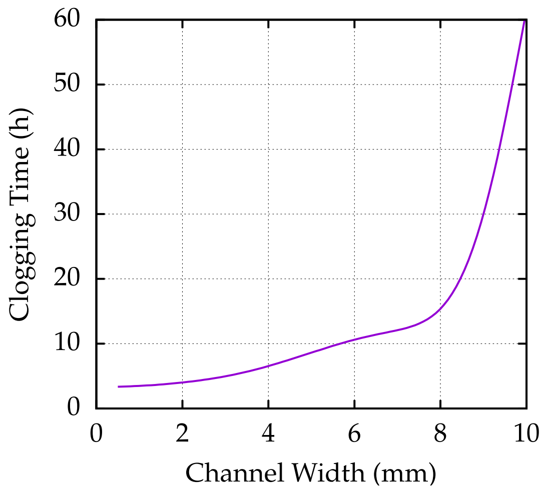

Figure 3—Clogging time dependence on channel width.

Returning to the question of clogging, we examine the time at which the channel becomes blocked. The results of this simulation can be found in Figure 3. For small channels, the clogging time increases with the width since a thicker condensate layer is required to clog the channel. However, for channels wider than 8mm, the clogging time greatly increases as the transport of SiO becomes dominated by the flow of the gas, and the SiO is less able to reach the surface. The clogging time measured in the simulations is approximately twice as large as measured in industrial furnaces. There are a few possible explanations for this. First, the values of the parameters of the model are not accurately known at the high temperatures in a furnace. Secondly, the channels in the charge form a network of connections, whereas we've modelled a single rectangular channel. Lastly, our model only considers the most influential physical process of the condensate growth, but, other physical phenomena may be important. The inclusion of these other processes in the model may decrease the clogging time predicted to better match what is seen in an industrial setting.

Conclusions

We developed a mathematical model for the growth of the condensate in channels within the charge of a silicon furnace. We found that, for narrow channels, the condensation reaction takes place primarily in the lower region of the charge, which causes a prominent peak to grow. We also found that narrow channels will become clogged with condensate much faster than wide channels.

The next steps in exploring the model would be to relax some of the simplifying assumptions such as those related to the reaction rate and form of the condensation. This would make the numerical solution much more challenging and computationally expensive, but would give rise to more representative physics.

Potential Impact

Our model has the potential to enable Elkem to understand the parameters and processes that contribute to the growth of condensate layers in their silicon furnaces, which will allow them to tune the process for better efficiency and higher yield.

Aasgeir Valderhaug, Director of Research and Development at Elkem, said:

> *The clogging of silicon furnaces due to gas condensation is a challenge for Elkem, since it hinders optimal chemical reaction patterns in the furnace due to nonuniform gas flow and raw material descent. Through the development of a mathematical model considering gas flow, condensation, and temperature, Brady has given us insight into the spatial profiles of clogging and how this varies with the size of the gas channels. This is valuable work and is a step towards better understanding of our process.*

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