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COMPUTATIONAL FLUID DYNAMICS MODEL OF ELECTRIC FURNACE FOR SMELTING NICKEL CALCINE

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ABSTRACT

A computational fluid dynamics (CFD) model was developed to study the interaction of the freeboard and calcine layer in an electric furnace that produces a nickel-copper sulphide matte. This interaction significantly affects energy efficiency, petroleum coke consumption, SO_2 and CO_2 emissions, and process integrity. Carbon monoxide emanates from the calcine layer and combusts in the freeboard. High ingress air flow rates are currently required to help keep the calcine from overheating and melting, resulting in a significant energy loss and a large off-gas flow that increases potential SO_2 removal costs. The CFD study illuminated a mechanism by which overheating from the freeboard could contribute to the loss of the calcine layer by repeatedly removing its top surface. The model showed how the CO combustion and, consequently, the distribution of heat in the freeboard are dominated by the ingress air flow. Finally, it was found that the calcine layer should be considered a moving material rather than just a static heat-conducting layer despite only a small downward velocity and that this movement is primarily responsible for keeping the top calcine surface cool.

INTRODUCTION

The 43-MW-electric furnace, 30 metres long by 10 metres wide, makes use of six in-line Soderberg electrodes to transfer heat to the slag for nickel-copper smelting (McKague and Norman, 1984). A schematic is shown in Figure 1. The electrodes are immersed approximately 30 cm into the slag layer. To protect the smelting process from the oxidizing conditions in the freeboard and to reduce iron, a 0.5 meter-thick calcine layer mixed with petroleum coke is maintained between the freeboard and slag. Maintaining the calcine layer in a “black top” (solid and cool) condition is critical to the process integrity. Moreover, the interaction between the freeboard and the calcine layer has a direct impact on energy efficiency, coke consumption, and SO_2 and CO_2 emissions. The current oxidizing conditions in the freeboard, combined with the emanation of CO from the calcine layer, result in a heat release of approximately 25 MW in the freeboard, which tends to promote the direct burning of coke and melting of the calcine layer. The direct burning of coke leads to excessive coke consumption and CO_2 emissions and melting of the calcine layer leads to excessive energy use and low metal recoveries. The operators endeavour to maintain the top surface of the calcine layer at a temperature of 550ºC. (This temperature is indirectly measured with thermocouples in the freeboard.) High ingress air flows are currently required to keep the freeboard from over-heating, to maintain the black top calcine layer. This results in a high off-gas flow, leading to significant energy loss from the system with reduced opportunity for heat recovery, and making potential SO_2 removal more costly.

The objective of this study is to understand the behaviour of the freeboard and calcine layer, and their interaction, to help develop a strategy to reduce the freeboard off-gas flows while still protecting the calcine layer. The analysis employs a combination of computational fluid dynamics and measured furnace operating data.

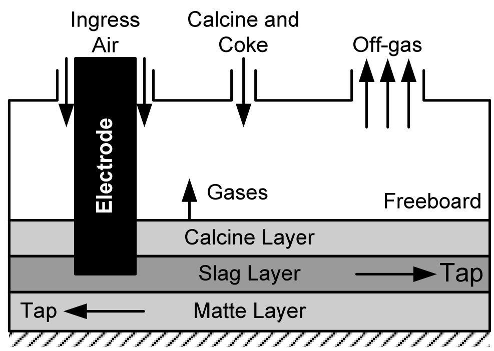


Figure 1: Schematic of the electric furnace.

CFD MODEL OF THE FREEBOARD AND CALCINE LAYER

In devising the model to represent the freeboard and calcine layer, the freeboard off-gas flow rate, composition and temperature were considered as well as the feed rate and properties of the calcine. This was critical to finding the appropriate description for a CFD framework and resulted in the creation of separate but interacting models for the freeboard and calcine. For all CFD calculations, the ANSYS-CFX software was used.

Furnace operation and preliminary consideration

Measurements of off-gas flow rate, temperature, and composition were provided by Xstrata and are summarized in Table 1. It was assumed that the ingress air is at 25ºC and 80% relative humidity. Assuming that all the CO_2 in the off-gas originated as either CO or CO_2 from oxidation of coke in the calcine layer, the off-gas measurements permit the determination of the gas flows emanating from this layer. It is found that the CO flow rate is 2.54 kg/s, the CO_2 flow rate is 0.260 kg/s, and the H_2O flow rate is 0.704 kg/s. Considering chemical equilibrium, this CO/CO_2 molar ratio of 15.3 is unusually high, which might indicate that direct combustion of coke is occurring. The CO flow rate corresponds to a heat release rate of 25.6 MW upon combustion in the furnace freeboard and, given the matte-end and slag-end off-gas temperatures, the heat transfer to the calcine can be determined. It was found that, in order for the off-gas temperature to be about 500ºC as indicated in Table 1, about 12.5 MW must be absorbed by the calcine (heat loss through the roof and walls of the furnace is relatively small). The remaining heat, 13.1 MW in this analysis, is carried by the off-gas.

	Matte-end off-gas	Slag-end off-gas
Flow rate [kg / s]	9.8	19.5
T [°C]	501	468
O2 [vol%]	15.4	13.0
CO2 [vol%]	6.7	11.1
CO [vol%]	0.1	0.1
SO2 [vol%]	0.3	0.3
N2 [vol%]	73.8	68.2
H2O [vol%]	3.7	7.3

Table 1: Measured off-gas flow rates, temperatures, and compositions.

The bottom of the calcine layer is in contact with the molten slag, where the temperature is approximately 1200ºC. New calcine material at 500ºC is added on top of the layer at a rate of 25 kg/s (90 tonnes per hour). The calcine layer does not conduct electricity (Sheng et al., 1998) so none of the 43 MW electric power heats the calcine directly. It will be shown that 39 MW is required to raise the calcine temperature from 500ºC to 1200ºC, including 15 MW for melting and endothermic reactions. From the above analysis, 12.5 MW of this 39 MW comes from the freeboard, so 26.5 MW would have to be transferred from the slag below. These overall heat balance numbers will be examined in the CFD analysis.

The calcine mass flow of 25 kg/s translates into an average downward velocity, V, of 0.083 mm/s, carrying heat with it. (The area is 300 m^2 and the density, ρ, is 1000 kg/m^3.) The question then arises as to whether heat conduction in the layer or heat carried by the downward moving calcine is more important. To estimate the relative importance, the dimensionless Peclet number, $\rho c V/(k/L)$, which is a measure of the heat carried by the moving calcine divided by the heat carried by conduction, is calculated and is found to vary between 4.8 near the bottom of the layer where the calcine is molten and 48 further up where the calcine is solid. (This calculation is based on a heat capacity, c, of 1154 J/(kg·K), a calcine layer thickness, L, of 0.5 m, and a thermal conductivity, k, of 1 W/(m·K) in the solid and 10 W/(m·K) in the liquid.) Therefore, the heat transferred by the downward flow of calcine is likely dominant throughout most of the layer and is at least comparable to the conducted heat transfer at the bottom of the layer. The only missing element from this analysis is the flow of gases through the layer. If it is assumed that most of the gases are produced near the bottom at the temperature for which peak reactions occur, 1020ºC, and emerge from the top of the calcine layer at 550ºC (in thermal equilibrium with the solid), then the maximum heat transferred to the calcine layer from the 3.67 kg/s flow of gases would be 2.3 MW. For a comparison of energy, this quantity is 5.9% of the 39 MW transferred to the calcine to raise it from 500ºC to 1200ºC and is, therefore, of secondary importance.

The Peclet number calculation showed that the calcine layer must be modelled as a downward moving and conducting layer with new material being added on top. The CFD framework is not currently capable of combining this type of calculation with the freeboard so separate but interacting calculations are carried out—a three-dimensional freeboard calculation and a one-dimensional calcine layer calculation. Heat and mass flows between the two are matched as boundary conditions of the respective calculations.

Model of the furnace freeboard

The three-dimensional steady state freeboard CFD model, illustrated in Figure 2, is bounded by the walls, roof, electrodes, and the top of the calcine layer. The walls, roof, and electrode surfaces are specified as adiabatic. The calcine surface temperature is specified to be 550ºC, which is the temperature for which the operators aim. Given this temperature-specified boundary condition, the tendency of the calcine to overheat is inferred from the calculated heat flux to the surface. The slag-end and matte-end off-gas mass flows are prescribed according to the measured data. Humid air is allowed to flow into the freeboard through total pressure-specified inlets representing various ports, pipes, and gaps. The largest gaps exist between the roof and electrodes as well as between the roof and the slag-end wall. Smaller pipes and ports are located toward the matte-end. The gases CO, CO_2, H_2O, and SO_2 flow from the calcine surface into the freeboard in the estimated distribution shown in Figure 3 (the overall flow rates were ascertained from the off-gas measurements, as discussed).

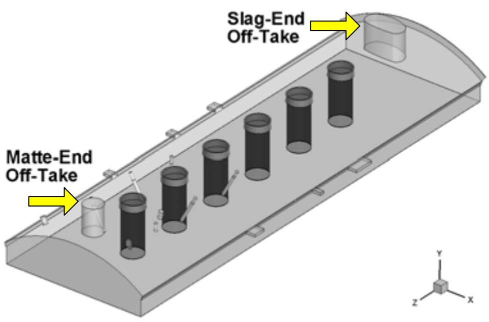


Figure 2: The freeboard CFD model geometry.

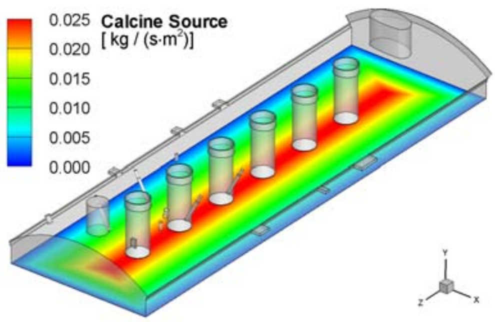


Figure 3: The prescribed distribution of gas flow from the calcine.

Turbulence is accounted for by the standard k-ε model. For combustion, CO is oxidized to CO_2 according to the lesser of the rates of the Eddy Dissipation Model that accounts for mixing and a finite rate chemistry model that accounts for chemical kinetics. The CO oxidation kinetics are those of Dryer and Glassman's study (1973)—atmospheric CO-O_2 reaction in the presence of water for temperatures ranging from 1030 K to1230 K. Radiation is calculated using a Monte Carlo model and the absorption coefficient of 0.14 m^{-1} is estimated for the dust-filled enclosure.

Model of the calcine layer

In the one-dimensional calcine model, the 25 kg/s calcine addition enters at 500ºC and is immediately exposed to a 7 MW heat source representing the heat from the freeboard (a result from the freeboard CFD calculation, not the 12.5 MW inferred from the off-gas measurements). The calcine moves and conducts heat. The total heat sink accounting for melting and endothermic reactions is determined from the enthalpy versus temperature plot in Figure 4 (a), which was provided by Xstrata (Coursol and Tripathi, 2008). The total heat sink, 15 MW, is the height (enthalpy per unit mass) of the vertical portion of the curve multiplied by the calcine feed rate of 25 kg/s. A temperature-dependent heat sink, shown in Figure 4 (b), is then applied throughout the calcine and is scaled to provide the total 15 MW sink. It is estimated based on information provided by Xstrata (Coursol and Tripathi, 2008), which showed that the intensity of endothermic reactions and melting is highest between 990ºC and 1050ºC, peaking at 1020ºC. The temperature-dependent conductivity was also provided by Xstrata (Coursol and Tripathi, 2008) and is shown in Figure 4 (c). The heat capacity of the calcine material, 1154 J/(kg·K), is determined from the slope of the line between 500ºC and 1020ºC in Figure 4 (a). To simplify, the flow of gases through the layer is neglected because it was shown that its thermal energy flow is relatively small compared to the total energy transferred to the calcine.

From Figure 4 (a), it is found that 39 MW is required to heat the 25 kg/s of calcine from 500ºC to 1200ºC. Since, in this analysis, 7 MW comes from the freeboard, the heat transferred by conduction from the slag layer to the calcine layer must be 32 MW. This heat source is applied at the bottom of the calcine layer where the material flows out. The temperature at the bottom of the calcine layer is then a result of the calculation, not a boundary condition. A summary of the energy and mass flows in the calcine layer model is provided in Figure 5.

RESULTS

The freeboard model results are presented first, followed by the results of the calcine model. Then the interaction between the two models, representing the interaction of the freeboard and calcine, is analysed.

Freeboard model results

A summary of the calculated ingress air mass flows is provided in Figure 6. It was found that 76% of the ingress air enters the freeboard through the electrode-roof gaps and 11% enters through the gap between the roof and slag-end wall, for a total of 87%. The remaining ingress air enters through the other pipe and port openings in the roof. The calculated gauge pressure in the freeboard is -60 Pa, which falls within the measured operating range.

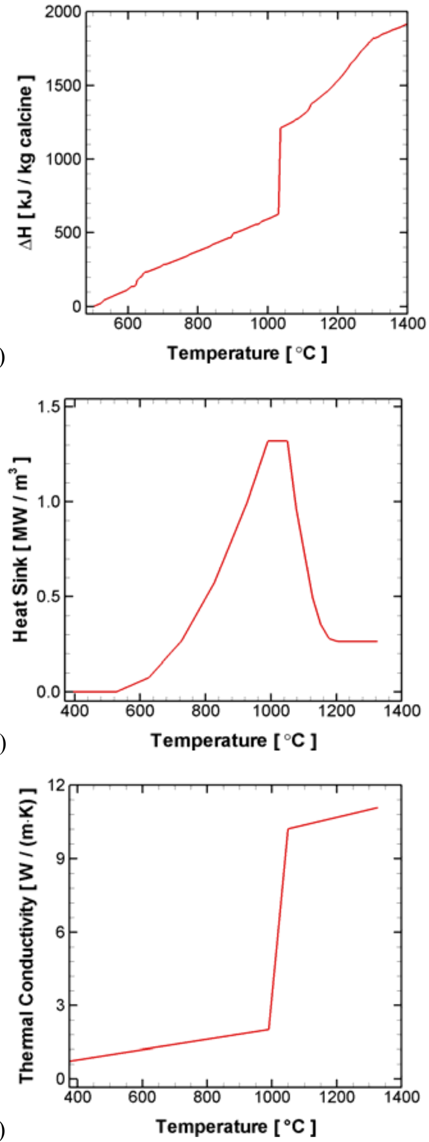


Figure 4: For the calcine: (a) enthalpy versus temperature, (b) heat sink versus temperature, and (c) thermal conductivity versus temperature.

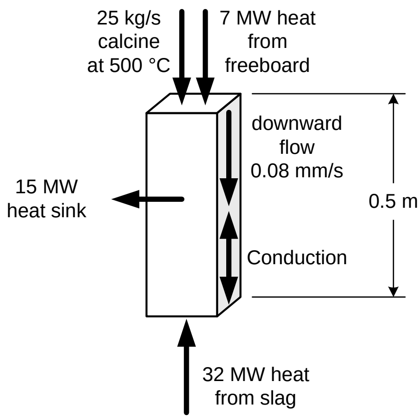
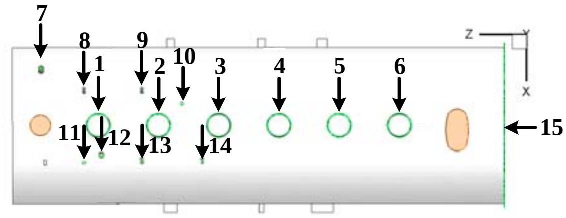


Figure 5: A summary of the one-dimensional calcine layer model.



1: 12.6%	5: 12.5%	9: 0.9%	13: 1.1%
2: 12.6%	6: 12.5%	10: 1.4%	14: 1.0%
3: 12.7%	7: 3.9%	11: 1.4%	15: 10.7%
4: 12.6%	8: 0.9%	12: 3.2%	

Figure 6: Ingress air mass flows as a percentage of the total ingress air flow. The furnace is viewed from the top. Green openings are inlets and orange openings are outlets.

The freeboard flow is shown in Figure 7, where it is found that the ingress air flow dominates over the calcine gas flow and therefore controls the mixing and combustion of CO. The ingress air coming from the electrode-roof gaps flows down along the electrodes like an annular jet, striking the calcine surface. It spreads out over the surface at approximately 6 m/s, mixing with the gases from the calcine layer, whose speed is at most 0.1 m/s. Figure 8 shows the freeboard temperature at a vertical plane through the electrodes and a horizontal plane 5 cm above the calcine surface, where the control of ingress air in the combustion of CO is apparent. Figure 9 shows the resulting heat transfer to the calcine layer, including the contributions by radiation and convection. Heat transfer is found to be dominated by radiation, except for the local cooling around the electrodes. Overall, 92% of the heat flux is from radiation. Comparing Figures 8 and 9, it is found that there is a strong correlation between the ingress-air-dominated combustion of CO and the resulting heat transfer to the calcine, which is higher toward the walls of the furnace.

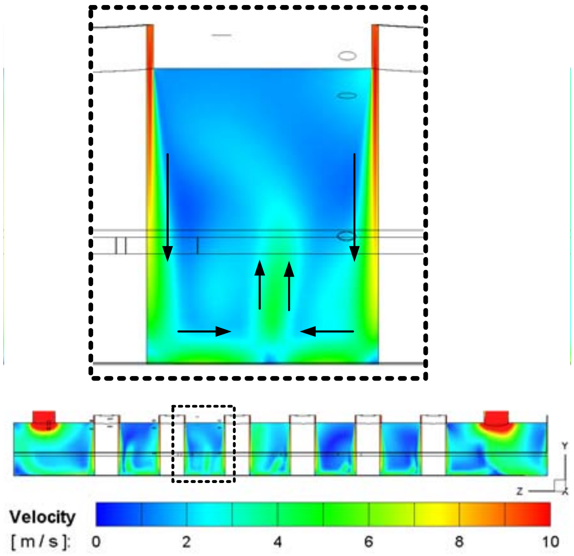


Figure 7: Flow velocity in the freeboard at a vertical cut along the furnace centre.

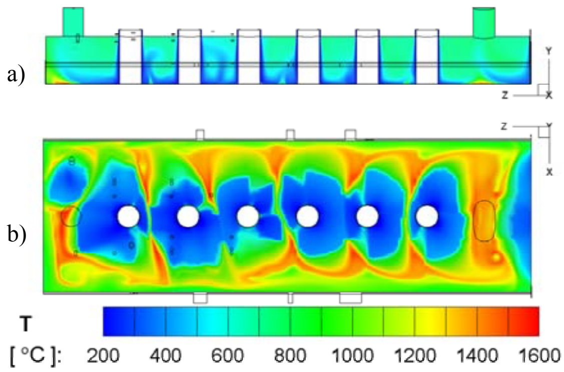


Figure 8: Temperature in the freeboard: (a) at a vertical cut along the furnace centre, and (b) at a horizontal cut 5 cm above the calcine top surface.

It should be emphasized that the heat flux in Figure 9 represents only the effect of the freeboard on the calcine layer. For example, small glowing rings of calcine material observed around the electrodes are not captured in the model results. The glowing rings are believed to be caused by effects not currently in the model including the high thermal conductivity of the electrodes (Bermudez et al., 1998), which conduct heat from the slag below, and a buoyancy-driven upward flow in the molten slag layer around the electrodes (Sheng et al., 1998).

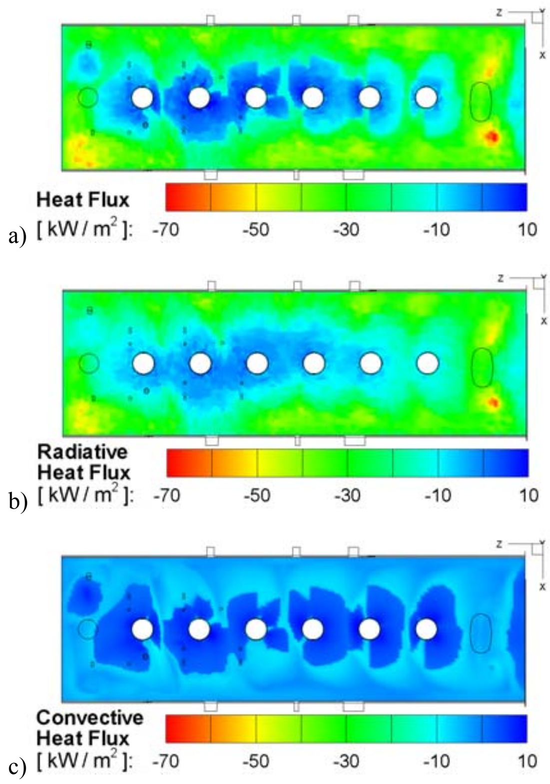


Figure 9: Heat flux to the calcine top surface from the freeboard. Negative numbers indicate that the freeboard is heating the calcine and positive numbers indicate the opposite. (a) Total heat flux, (b) radiative contribution, and (c) convective contribution.

The total heat transferred to the calcine, determined by integrating over the entire surface, is found to be 6.4 MW, in contrast to the 12.5 MW that was inferred earlier from the off-gas measurements. Since the calculated heat transfer could be highly dependent on the radiation absorption coefficient and this radiative property is difficult to precisely determine, the calculation was repeated with the absorption coefficient doubled from 0.14 m^{-1} to 0.28 m^{-1}. The total heat transfer was then found to be only slightly higher at 7.0 MW and, therefore, it seems unlikely that the heat transfer could actually be 12.5 MW. Comparing the off-gas measurements, from which the 12.5 MW value was inferred, to typical operating data revealed that the measured off-gas flow rates might be too low, which would lead to an erroneously high inferred heat transfer. Therefore, it is concluded that the heat transfer to the calcine layer is at most 7.0 MW, considering that increased ingress air in the CFD model would result in a cooler freeboard and less heat transfer to the calcine.

The remaining thermal energy (25.6 MW minus 7.0 MW) is carried out of the freeboard by the off-gas and consequently the temperature is predicted to be 665ºC. This exceeds the measured temperature and, again, suggests that the off-gas flow rate was actually higher than measured. If the off-gas flow would be higher, it could carry the 18 MW of energy at a lower temperature. Predicted freeboard temperatures are also found to be generally higher than the measured values provided by Xstrata, which is consistent with the higher predicted off-gas temperatures.

The predicted off-gas temperatures and compositions are compared with the measured values in Table 2. The measured CO_2 and H_2O volume fractions are higher in the slag-end off-gas whereas they are evenly distributed in the CFD prediction. This suggests that it is not the flow dynamics but, rather, a higher rate of smelting toward the slag-end that causes the CO_2 and H_2O compositions to be higher.

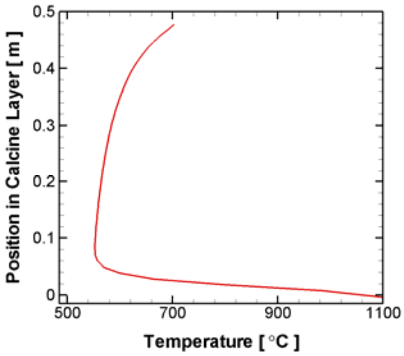
	Matte-end off-gas		Slag-end off-gas	
	Measured	Predicted	Measured	Predicted
T [°C]	501	657	468	673
O2 [vol%]	15.4	13.7	13.0	13.7
CO2 [vol%]	6.7	9.9	11.1	9.9
CO [vol%]	0.1	0.0	0.1	0.0
SO2 [vol%]	0.3	0.3	0.3	0.3
N2 [vol%]	73.8	70.0	68.2	70.0
H2O [vol%]	3.7	6.1	7.3	6.1

Table 2: Measured and predicted off-gas compositions.

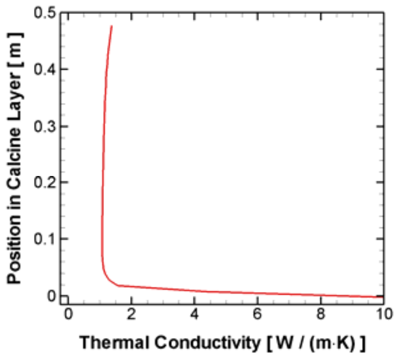
Calcine model results

The predicted calcine layer temperature, thermal conductivity, and Peclet number profiles are shown in Figure 10. The predicted temperature at the bottom of the calcine layer is 1263ºC, which is close to the expected value and suggests that the modelling approach is reasonable. Although the temperature of much of the calcine layer is around 550ºC, the top of the calcine layer has a higher temperature, approximately 700ºC, because of its exposure to the freeboard. The top surface of the calcine layer is a mix of new material at 500ºC and the heated material at 700ºC. Taking an average of the two, the temperature of the top surface would likely be 600ºC. The higher temperature of the top surface compared to the material below suggests that heating from the freeboard could contribute to the loss of the calcine layer. Over-heating by the freeboard could raise the top surface temperature of the calcine layer to a level that would promote direct combustion of the coke and melting which would in turn expose the calcine below to undergo the same coke combustion and melting process. Eventually the entire layer could be lost.

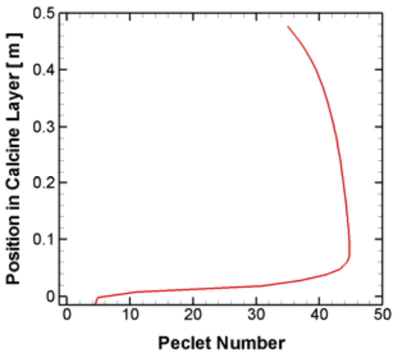
The model also suggests the means by which the top of the calcine is cooled. Recall that the Peclet number is very high for solid calcine and, therefore, heat transfer is dominated by the downward movement of material carrying heat with it and conduction is minimal in comparison. Therefore, the top surface of the calcine is cooled mainly by the addition of new material at 500ºC.



a)



b)



c)

Figure 10: Calcine model results: (a) temperature, (b) thermal conductivity, and (c) Peclet number, as a function of height above the slag.

Freeboard/calcine interaction

Knowing the heat flux from the freeboard, the mass flux of calcine, and that heat transfer in the solid calcine is dominated by the downward movement of material rather than by conduction, the average temperature of the calcine top surface can be calculated from the enthalpy versus temperature graph in Figure 4 (a). For a freeboard heat transfer of 7.0 MW and a calcine mass flow of 25 kg/s, the heated temperature is found to be 725ºC, and given that the top surface is a mixture of new and heated material, the temperature is likely to be 612ºC, which is close to the 600ºC value from the calcine model. The ability to calculate the calcine surface temperature from the freeboard heat flux and the calcine mass flux also permits the re-interpretation of Figure 9 (a). The heat flux may be re-interpreted as the calcine mass flux that is required to maintain the calcine surface temperature at 550ºC (an average of new material at 500ºC and heated material at 600ºC). This result is shown in Figure 11, which suggests the locations and the rates at which the incoming calcine material should be added. Again, it should be emphasized that this represents only the effect of the freeboard on the calcine. There are other factors involved in determining the locations at which the incoming calcine should be added. Integrated over the whole area, the total calcine addition rate is found to be 55.3 kg/s, which is about twice the actual rate of 25 kg/s. The result that calcine would have to be added at a rate double the actual suggests that the calcine surface temperature is actually higher than 550ºC. It is likely closer to 600ºC, as suggested by the calcine model.

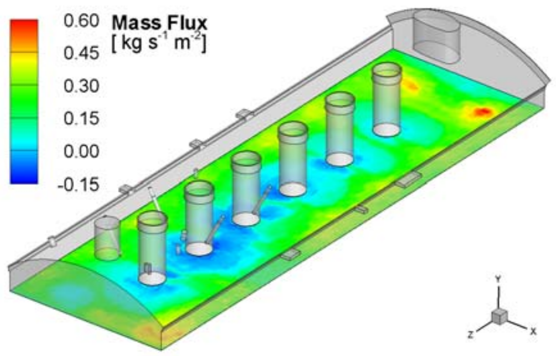


Figure 11: Calcine mass flux required to maintain a surface temperature of 550 °C.

CONCLUSIONS

A CFD study of an electric furnace for smelting nickel calcine was carried out, focussing on the interaction of the freeboard and calcine layer. The method consisted of separate but interacting calculations of the freeboard and calcine and a key component of the analysis was the available operating and property data. The model has shown to be a useful tool that will help devise strategies to reduce the furnace off-gas flow rates while still protecting the calcine layer.

It is concluded that the ingress air flow dominates the mixing and combustion of CO in the freeboard, ultimately determining the distribution of heat flux to the calcine layer. It is found that approximately 7 MW of the 25 MW heat release in the freeboard is transferred to the calcine layer, mainly by radiation, with the remaining heat carried by the off-gas flow. Comparison of the predicted off-gas composition and the measured composition suggests that the difference in measured gas composition between the slag-end and matte-end off-takes is not a result of the freeboard flow dynamics but, rather, a consequence of more smelting occurring toward the slag end.

Analysis of the calcine layer showed that it should be considered a moving and conducting material, not simply a static conducting layer, even though the average downward velocity is only about 0.083 mm/s (30 cm/h). The study found that the top of the calcine layer could repeatedly overheat, eventually contributing to the loss of the entire layer. The study also revealed that, since heat conduction is not significant in the solid calcine, the principal method for cooling, aside from drawing increased ingress air to cool the freeboard (which is counter to the desired outcome), is the addition of new calcine material on top.

Given the results of the freeboard and calcine models, the calcine mass flux distribution required to maintain a surface temperature of 550ºC may be inferred. This distribution suggests the locations over which the new calcine material should be added to protect the calcine layer from overheating. The fact that the total addition rate of calcine material predicted from this method is twice the actual rate suggests that the calcine surface temperature is higher than 550ºC and is closer to 600ºC.

Some discrepancies between model results and measurements/observations were identified. Further coordination between measurements and modeling assumptions may help to resolve discrepancies identified in this paper.

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