

CHAPTER 11 CONCLUSION

11.1 OBJECTIVES AND APPROACH

The objective of this work was to study and characterise the dynamic behaviour of the freeze lining and slag bath, study and characterise the interactions between freeze lining and slag bath, and to study the compositional invariance of the slag close to the stoichiometric M_3O_5 line and possibly determine the mechanism causing this phenomenon.

The approach used to achieve the objectives focused on mathematical modelling. Process models of the freeze lining and furnace sidewall, of the slag bath crust and of the entire smelting process were constructed. These models were used to study the phenomena of interest by conducting numerous experiments. The experimental results were processed and converted into series of graphs to display the behaviour of the process or of a particular part of the process during the experiments.

11.2 CONTRIBUTION OF THIS WORK

11.2.1 Process Models

The process models developed and documented in CHAPTER 3, CHAPTER 4 and CHAPTER 5 do not, strictly speaking, have any value in their own right. Such models only become valuable through their application to the study of specific problems and phenomena as was done in this work. The details on these models presented in this text may however provide a useful starting point for modelling work by other workers.

The models can also be applied to study further issues relevant to ilmenite smelting and, by including the appropriate material property data, to other similar processes. All the models were developed with broader future application in mind.

One aspect that must however be kept in mind is the fact that specific furnace dimensions and material property data were used in the versions of the models presented here. These data items must be replaced with data that is representative of an actual process for the models to be directly applicable to such a process. This fact must also be taken into account when viewing and interpreting experimental results presented in this text.

Given the new insights presented in CHAPTER 10, some of the assumptions made in the formulation of the ISFP model in CHAPTER 5 appear to be critically invalid. The first of these is Assumption 5.1 that assumes the slag bath, metal bath and furnace freeboard to be isothermal. The proposed mechanism behind the observed compositional invariance relies on the slag and metal baths having different temperatures. Such a temperature difference does, of course, occur in reality. The second is Assumption 5.2 that assumes the slag bath to be ideally mixed. The proposed mechanism will cause concentration gradients to form in the slag bath.

The ISFP model should be updated to incorporate the proposed mechanism. This will make the model significantly more representative of the actual process, and it will rid the model of restrictions such as that of the approach used to constrain the liquid slag composition close to the stoichiometric M_3O_5 line.

Another restriction that is worthwhile addressing is the one-dimensional nature of the FLC model. This prevents the model from describing variations in metal and slag bath levels, resulting in a significant limit in the degree to which the model is able to describe the dynamic behaviour of an actual furnace.

Finally the use of actual plant data to adjust the model parameters of the various models can improve greatly the accuracy with which these models describe reality. This will have to be done in co-operation with an organisation operating one or more ilmenite-smelting furnaces.

11.2.2 Interactions between Freeze Lining and Slag Bath

The experimental results displaying slag bath and freeze lining behaviour highlighted, and perhaps reconfirmed, the fact that the behaviour and co-existence of, and the interaction between the slag bath and freeze lining are governed by two major influences.

The first is the influence of the phase chemistry of the TiO_2 - FeO - Ti_2O_3 system. Solidification and melting result in the formation of phases as predicted by the phase diagram. This is of course expected for the models because of the fact that all of them have a strong thermochemical foundation. The fact that the models were able to produce realistic results perhaps confirms the dominant influence of phase chemistry and the drive towards thermodynamic equilibrium in the actual process. This notion is supported by the fact that the mechanism proposed to cause the observed compositional invariance is also strongly founded on the influence of phase chemistry and the drive towards equilibrium.

The second influence is that of heat transfer. In a situation where more energy is being discharged into the system than can be consumed by reduction reactions and removed via heat loss avenues, the freeze lining will start melting away to increase the rate at which heat can be conducted towards the outer surface of the furnace wall. In an opposite situation the freeze lining will start to grow thicker. The response of the freeze lining is of course not the only effect of such situations. Heat losses through the lower sidewalls and hearth, and from the top of the slag bath will also change, as will the characteristics of reduction reactions taking place (to a limited extent).

The conclusion is therefore that the slag bath and freeze lining behave as expected once one takes cognisance of the thermochemical and heat transfer characteristics of the system.

11.2.3 Process Mechanisms

A mechanism that explains the compositional invariance of slag close to the stoichiometric M_3O_5 line was proposed in CHAPTER 10. This mechanism points at the drive towards thermodynamic equilibrium as being a major influence in the process.

This contradicts the speculation in CHAPTER 5 about reaction kinetics and the possibility of it being the cause of the compositional invariance. These speculations are believed to be much further from the truth than the mechanism proposed in CHAPTER 10. Kinetics may indeed account for some yet unexplained

observations, but its influence is likely to be much less determining of general process behaviour compared to the influence of thermochemistry.

As a result of the above-mentioned mechanism, some questions arise about the mechanisms behind other phenomena in the process. The production of iron metal due to contact between liquid slag and reductant on the slag bath surface, and the travel of iron metal droplets from the slag bath surface, through the slag bath and into the metal bath become less probable. These phenomena may in fact occur, but to a limited extent.

There are still some unanswered questions about how the level of carbon in the metal bath is achieved and sustained. Reasoning provided in CHAPTER 10 regarding this issue is intuitively congruent with DC furnace operation, but not necessarily with AC furnace operation. In general, significant uncertainty still exists about reactions and process mechanisms in the turbulent, high-temperature zone underneath the electrode.

11.2.4 The Nature of Thermocouple Signals

The thermal response of the freeze lining and furnace wall were analysed and included in the result set of virtually each experiment conducted. Of these analyses, the work in CHAPTER 6 probably best characterises the nature of this response.

A significant observation was the asymmetry of the thermal response. Temperatures in the wall respond quicker when the freeze lining becomes thinner than when it grows thicker. This is an important fact to consider when developing an operating strategy or an automatic controller to regulate freeze lining thickness.

Perhaps more striking than the asymmetry of the thermal response was its slowness. This can be seen in Figure 87 (page 171). The sluggish response of these signals leaves one in a 'catch 22' situation regarding the positioning of thermocouples in the furnace sidewalls. By placing a thermocouple too deep, one runs the risk of destroying it when the freeze lining melts away. Conversely, placing it far away from the refractory hot face may prevent one from detecting that the freeze lining is melting away and taking action to prevent damage to the refractory wall. One may decide to view thermocouples as expendable, but repeated removal and installation of thermocouples will also inevitably inflict damage on the refractory wall. Placement of thermocouples in the furnace sidewalls remains a difficult decision to make.

11.3 OPPORTUNITIES FOR FUTURE WORK

The work done in this project provides a platform for future work. Such work can include both improvements to the models presented here, and application of the current and improved versions of the models.

11.3.1 Model Improvements

The conductor models developed in CHAPTER 3 and CHAPTER 4 can be extended from the current one-dimensional formulation to a two-dimensional one. This will remove the restrictions that especially the FLC model places on the ISFP model. The ISFP model will then be able to describe varying slag and metal levels in the furnace. This will make the model more realistic in that it will be possible to 'operate' it in exactly

the same way that an actual furnace is operated. Such an improvement will also result in the model describing the dynamics of the process significantly better.

The proposed mechanism behind the observed compositional invariance and the additional insights into other mechanisms that were presented in CHAPTER 10 can be incorporated into the ISFP model. This will make the model more representative of the actual process and it will remove restrictions placed on the model by, for example, the method used to constrain the slag composition close to the stoichiometric M_3O_5 line.

The current work incorporated only four constituents (TiO_2 , Ti_2O_3 , FeO , and Fe_2O_3) in the liquid slag phase. Of these constituents Fe_2O_3 was never used here. In the liquid metal phase only carbon, oxygen, titanium and titanium oxide solutes were included. Many constituents that occur in reality were therefore omitted here to simplify matters. Such components can be included in the thermochemical data files to better model industrial process and produce modelling results with which operational and process personnel of ilmenite smelters can identify more easily.

The furnace dimensions and material properties of the refractory brick, ramming material and steel shell can be replaced with data of actual furnaces. This will immediately result in an improved representation of such processes. The various parameters of the ISFP model can also be tuned based on data from industrial furnaces. This will further enhance the accuracy with which the model is able to describe these processes.

11.3.2 Model Applications

The availability of an accurate process model creates a number of opportunities. In general it provides a 'virtual copy' of the process that one can use and experiment with to study various issues. Without such a model one would either have to resort to experimentation on the actual furnace or a smaller-scale furnace, or to experimentation on laboratory scale. Both these alternatives have benefits and disadvantages. However, they are both likely to be more time-consuming and possibly more expensive than a modelling study.

Firstly, the ISFP model can be applied as a simulation model within a process simulator. Such a simulator can then be used to develop and test a control system for controlling parameters such as freeze lining thickness, slag composition, and slag and metal inventory. This reduces the risks involved with implementing a controller on a furnace, since it has already been tested on an accurate computer-based representation of the process.

Further, the simulator can be used to evaluate the impact of different operating strategies on the process. This can again be done on the actual process also, but at a higher risk of damage and losses in production, and over a longer period of time. Numerous low-risk and relatively quick experiments can be done with a process simulator based on the ISFP model.

The simulator can also be used to evaluate the impact of different thermocouple placements given a specific furnace configuration, feed materials and control strategy. This will enable process engineers to be better informed and more objective when making decisions about the placement of thermocouples in furnace sidewalls.

A process simulator can be used for operator training. The benefits of this are again lower risk of damage and production losses, and a possible saving of time. An operator can be exposed to and tested on a wide range of process conditions and scenarios without running the risk of costly mistakes on an actual furnace.

The models developed here could also be adapted fairly easily for application to AC ilmenite smelting furnaces. The circular geometry should be changed to rectangular in the case of six-in-line AC furnaces. Other than that change, the models could most likely be applied as they are to AC smelting furnaces.