Infacon XVI: International Ferro-Alloys Congress,
Edited by A.N. Wærnes, G. Tranell, M. Tangstad, E. Ringdalen, and C. van der Eijk
SINTEF/NTNU/FFF, Trondheim, 27-29 September 2021

Electrical Conditions in 3-phase Submerged Arc Furnaces: Learning from the ElMet project

S.A. Halvorsen[1], M. Sparta[1], V.K. Risinggård[1], M. Fromreide[1],
[1]NORCE Norwegian Research Centre AS, Norway, svha@norceresearch.no

Keywords: Electrical conditions, submerged arc furnace, SAF, mathematical modelling, induction, eddy currents, proximity effect, metamodels

Abstract – ElMet is the short name for a competence project (2015-2020) on electrical conditions in 3-phase submerged arc furnaces (SAFs). In the project, NORCE has cooperated closely with The Norwegian University of Science and Technology (NTNU), University of Oxford, University of Santiago de Compostela, and the industrial partners, Elkem and Eramet Norway.

ElMet has focused on mathematical modelling, and a set of tools have been utilized:

- Basic equation analysis, together with very simplified models, have clarified fundamental aspects.
- 2D and 3D models have then supplied important overall insight.
- Finally, metamodels have enabled a link between physics- and data-based modelling.

The ElMet project has established a sound basis for understanding electrical conditions in SAFs, and proper tools have been developed and tested for future use:

- Flexible 3D simulations models to be applied for various case studies.
- A strong electromagnetic proximity effect for (almost) parallel currents has been discovered.
- Induced currents in the furnace steel shell carry information that might be utilized for identification of inner conditions.
- Metamodels, together with additional measurements, seem suitable for on-line use and to identify inner furnace conditions.

INTRODUCTION

Mathematical modelling has successfully been applied for various aspects of metallurgical processes. Nevertheless, due to all complexities in the processes, the design and operation of smelting furnaces are still to a large degree empirically based, and several process variations are not properly understood. Representatives from Eramet Norway, Elkem and Alcoa* identified a knowledge gap concerning the effects of 3-phase alternating current, including how the associated power distribution governs the chemical reactions and temperature distribution.

The knowledge-building project, "Electrical Conditions and their Process Interactions in High Temperature Metallurgical Reactors (ElMet)", 2015-2020, was then initiated. ElMet has been a challenging, multi-disciplinary project focusing on relevant mathematical modelling, with close cooperation between NORCE, the industrial partners, and researchers from The Norwegian University of Science and Technology (NTNU), University of Oxford, and University of Santiago de Compostela. Conceptually, the project has included research within:

- Basic understanding of electrical conditions for 3-phase submerged arc furnaces (SAFs)

---

* Alcoa left the ElMet project when they stopped their research project on developing a carbo-thermic process for aluminum production.

- Relevant models for overall view, case studies and design
- Metamodels – Combining physics- and data-based modelling
- Material data, verification

In the following, an overview of the learning from the project will be presented. In the ElMet project, we have studied various electrical aspects of (Fe)Si- and Mn-processes in circular furnaces with 3 electrodes and 3-phase electrical supply. Many results can, however, be transferred to other geometries and processes. In this paper, examples will mainly focus on large FeMn furnaces. Mathematical details are intentionally omitted.

BASIC UNDERSTANDING OF ELECTRICAL CONDITIONS

Mathematical models for alternating current (AC) consists of applying Maxwell's equations. To study the fundamentals, we have:

- Analyzed the equations
- Applied (very) simplified models, 1D and 2D models
- Clarified how linearity can be exploited

Basic equation analysis

We have assumed harmonic time variation and neglected higher harmonics. Depending on the conditions, Maxwell's equations can then describe:

- Electromagnetic waves
- High frequency AC
- Low/moderate frequency AC
- Direct current (DC), or strictly speaking AC that at any time instant looks like DC

Equation analysis revealed that two physical parameters are important, the electromagnetic wavelength, λ, and the skin depth, δ:

$$\lambda = \frac{c}{f} \qquad [1]$$

$$\delta = \sqrt{\frac{1}{\pi f \sigma_e \mu}} \qquad [2]$$

where c is the speed of light, f is the frequency (normally 50 Hz), σ_e is the electrical conductivity, and μ is the magnetic permeability.

The electromagnetic wavelength will be around 6 000 km, i.e., far bigger than the size of the furnace. Hence, electromagnetic waves and the corresponding terms in the equations can safely be ignored, c.f. for instance Halvorsen, Olsen, and Fromreide (2016). The resulting set of equations are well known as the low-frequency time harmonic Maxwell's equations (Bermúdez, Gómez and Salgado, 2014; Fromreide *et al.*, 2021a; Fromreide, 2021).

With this approximation, there will only be one relevant material parameter, δ, for each material. Further, the qualitative behavior of the electric conditions will depend on two types of non-dimensional parameters, aspect ratios and the ratio between a length/width and the skin depth:

$$(H_i/L_j)^2 \text{ and } (H_i/\delta_k)^2 \qquad [3]$$

where H_i and L_j are two geometric parameters (e.g., length, height, width, diameter, …) and δ_k is the skin depth for material number k. The number of parameters depend on the number of materials involved and the geometric complexity. The qualitative behavior will depend on whether such parameters are very large, around one, or very small.

The conditions for a single conductor, are well known. If it is long and thin, $(H/L)^2 \ll 1$, where H is the thickness or diameter and L is the length, then the current distribution may only vary across the conductor. Variations in the length direction are only possible in small regions at both ends. If the skin depth is large compared to the width/diameter, $(H/\delta)^2 \ll 1$, the current will distribute uniformly on the cross section and AC will behave like (slowly varying) DC. In the opposite extreme, $(H/\delta)^2 \gg 1$, the electrical current will be confined to a thin layer along the boundary/periphery of the conductor. If the parameter is around 1, the current will distribute on the whole cross section with higher concentration at the boundary/periphery than in the center.

It should be noticed that the ratios are squared in the relevant non-dimensional equations. They are therefore expressed as squared ratios in [3]. This quadratic property implies that the behavior can change significantly due to comparatively small variations. Roughly, a change by a factor 3 of a "non-squared" ratio, implies almost a factor 10 change in the "influencing" factor. If this factor is of order 1, the change can be dramatic. If on the other hand, the parameter is either very large or very small, the change can be negligible.

While the conditions are fairly easy to study for a single conductor, they are far more complex in a real furnace. In a large FeMn furnace, there will be regions where the ratio $(H/\delta)^2$ will be small (cold or moderately heated charge), moderate (coke bed), and large (electrodes, metal, steel shell).

Simple models in 2D and 1D – Proximity between adjacent currents

A (cartesian) 2D model was applied to study the basic electrical effects. This model included two electrodes, a flat coke bed (or slag layer), a metal layer, and regions with very low conductivities (e.g., cold charge materials). Computed power density from a simulation is shown in Figure 1. For a DC case, the current would "fill the whole cross section", i.e., we would get fairly uniform current and power distributions within the flat coke bed between the electrodes. The AC simulations showed, however, very uneven distribution, where the current in the coke bed had been "pushed away" from the metal layer. Between the electrodes there is a comparatively long "1D region" in the middle, i.e., the power distribution varies in the vertical direction while it is approximately constant in the horizontal direction.

Further analysis, using a 1D model, revealed that we had discovered a strong proximity effect between alternating currents in adjacent, "parallel", regions. The distribution of electric and magnetic fields (and hence also current and power) in one region will depend strongly on the properties of other regions. The coupling between the layers is due to the magnetic field. Hence, the strong proximity effect does not depend on electrical contact between the layers. (Electrical contacts can, however, be important to determine the current paths.)

Our studies have revealed that the distribution of parallel, alternating currents above a highly conductive metal layer differs strongly from the DC case. Also, this effect implies less current in the metal, compared to DC (Fromreide *et al.*, 2021a; Fromreide, 2021). But if the power generated in this region is small, compared to the total power, DC simulations may still be applied to compute a reasonable power distribution. The ElMet project has provided a tool for a check: We can apply a 1D model to estimate the power dissipated midway between two electrodes. Then the total power in the region can be approximated by assuming the same conditions for the whole volume between the electrodes. If this estimate shows negligible power, then DC simulations can be applied. If not, we recommend AC simulations. (Fromreide *et al.*, 2021a; Fromreide, 2021).

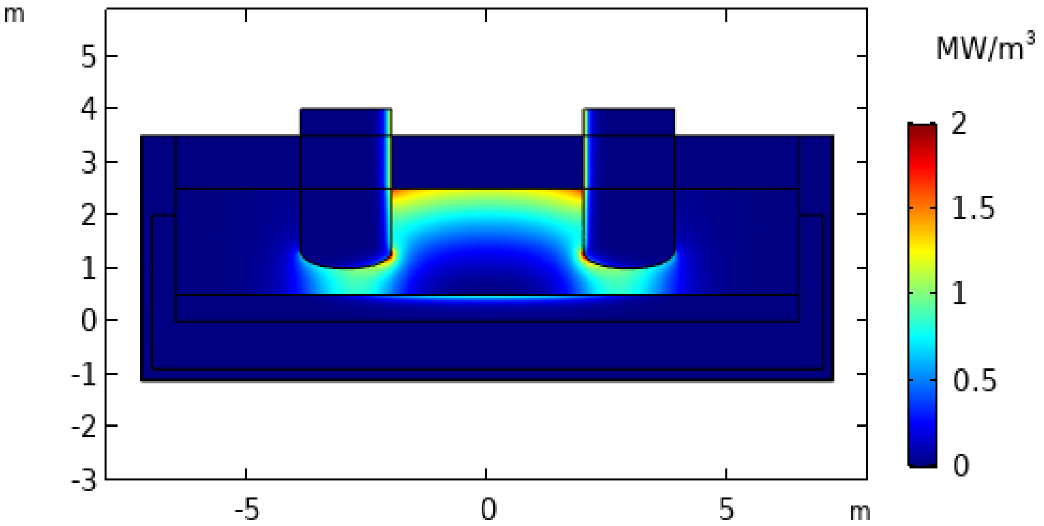

Figure 1: Typical distribution of AC power density in a simple 2D model**.**

The simple 2D model has been applied for various case studies and can be utilized to find how various parameters influence current and power distribution (Fromreide *et al.*, 2021a; Fromreide, 2021). The simple equation analysis revealed what parameters can be important, and that the conditions can depend strongly on whether such non-dimensional parameters are large, moderate (of order one) or small. The 2D model can then be applied to check how important various parameters are. 2D simulations are suitable to perform a large number of parametric studies. The results should be treated as indicative and we recommend that they are checked against some 3D simulations. In some cases, effects in 2D can be far stronger or weaker than in 3D.

The proximity effect between adjacent materials is also significant for the current distribution in a conductive carbon lining. There will be a strong coupling between a magnetic steel shell and the conductive materials inside the furnace (Fromreide, 2021). We recommend that this effect is studied when a furnace is relined.

Further details on the strong proximity effect between parallel currents can be found in Fromreide *et al.* (2021a) and Fromreide (2021).

Maxwell's equations – Linearity

Maxwell's equations are linear, which means that the computed electric and magnetic fields depend linearly on the input values. The current distribution will also be a linear function of input variables, while the power is a quadratic function. Due to this linearity, it is not required to solve the equations for all combinations of inputs.

For AC simulations the input current is normally specified for two electrodes. Due to current balance, the current is then given for the third electrode. Based on the linear property, one can compute the solution for two single-phase cases, and then find the solution for any current input (Fromreide *et al.*, 2021b). The procedure requires some arithmetic with complex numbers, but this is fairly easy to perform in COMSOL Multiphysics which we have applied (and hopefully also in similar simulation code). A demo example is shown in Fromreide *et al.* (2021b) and further details for AC simulations can be found in Fromreide (2021).

When selecting the input for the two electrodes, the appropriate phase shift must be chosen. The phase shifts are ±120° if and only if all electrode currents are equal. For almost equal currents, 120° might be appropriate.

If DC solver is relevant, three DC models can be combined as described by Halvorsen, Olsen, and Fromreide, (2016). Here, the three basic solutions are not independent. One of them can be found by combining the two other ones. Also, if the materials are symmetrically distributed, it is only required to compute the solution for one half furnace. The rest can be found by mirroring and rotation. (Halvorsen, Olsen, and Fromreide, 2016)

MODELS FOR OVERALL VIEW, CASE STUDIES AND DESIGN

2D versus 3D models – Proximity effects in electrodes

To get an overall view and perform studies that shall relate directly to real equipment and processes, adequate models need to be far more detailed (and realistic) than the 2D model shown in Figure 1.

In many cases, 2D models may be fully adequate. 2D axially symmetric models are, for instance, well suited for various electrodes problems, c.f. for instance Bermúdez, Bullón, and Pena (1998) and Feldborg, Larsen, and Halvorsen (2013). 2D cartesian simulation has also been applied for complete furnace simulations, e.g., by Karalis *et al.* (2016). We recommend that such 2D studies are supplemented with 3D simulations, e.g., as done by Karalis *et al.* (2020), or at least by some axially symmetric simulations. As stated above: Effects in 2D can be far stronger or weaker than in 3D.

Within the ElMet project we have made a comprehensive review of skin and proximity effects in electrodes (Herland, Sparta, and Halvorsen, 2019). This study includes various analytical models, that are compared to 2D COMSOL simulations. The effects are studied separately:

- Skin effect in a single electrode, including comparing AC and DC.
- Skin and proximity effect in one electrode, approximating the other two by line currents.
- Induced currents in steel shell when the three electrodes are treated as line currents.

Then all effects are combined in COMSOL simulations:

- 2D model including electrodes and steel shell
- 3D furnace model, to check how well the 2D models perform

The publication is a good example to show how simpler models can be very useful to acquire a basic understanding of the various effects, while more complete models are needed to check how well the simpler models work (Herland, Sparta, and Halvorsen, 2019).

DC versus AC

Direct current (DC) has often been applied to study current and power distributions in 3-phase AC furnaces, for instance by Darmana *et al*., (2012); Dhainaut (2004) Karalis *et al.* (2017), and Tesfahunegn *et al.* (2018). In an ElMet study we have shown that only two DC cases need to be solved to get the solution for *any* time instant, or to compute the distribution of the average AC power input (Halvorsen, Olsen, and Fromreide, 2016), when induction effects can be neglected.

DC is comparatively easy to understand and far more computationally efficient than full AC simulations (Halvorsen, Olsen, and Fromreide, 2016). DC solvers can therefore be preferential unless skin and proximity effects are important for the problem to be investigated. We strongly recommend that this is clarified before relying on DC solvers. Tesfahunegn, *et al.* (2020), has for instance compared AC and DC solvers for a model of a ferrosilicon (FeSi) furnace, and found only minor differences for their case studies. Our simple estimate, described in the previous chapter, is another method for clarification.

Flexible sample models for case studies

In the ElMet project, we have adapted Finite Element Method (FEM) models in COMSOL Multiphysics for FeMn and (Fe)Si furnaces. Figure 2 shows the geometry and material distribution for a 41 MW FeMn case study (Herland, Sparta, and Halvorsen, 2018). The geometry includes 1) air (including a sufficiently large region outside the furnace), 2) electrodes, 3) charge at some 400 °C, 4) charge at some 800 °C, 5) charge at some 1200 °C, 6) coke beds, 7) alloy, 8) carbon lining, 9) oxide lining, 10) steel shell, 11) steel roof. Figure 3 shows some alternative shapes for the coke beds. In these cases, we have not included a separate slag region.

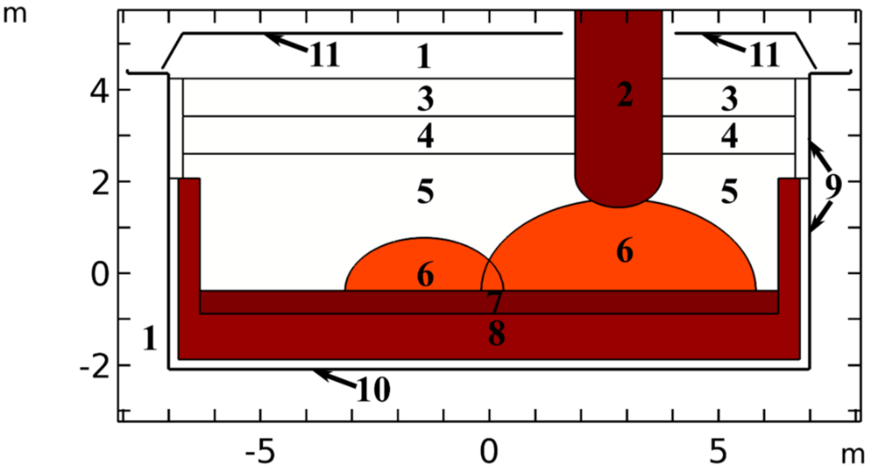

Figure 2: Material distribution in a model for a FeMn furnace. The figure shows a slice through one electrode and midway between the other two.

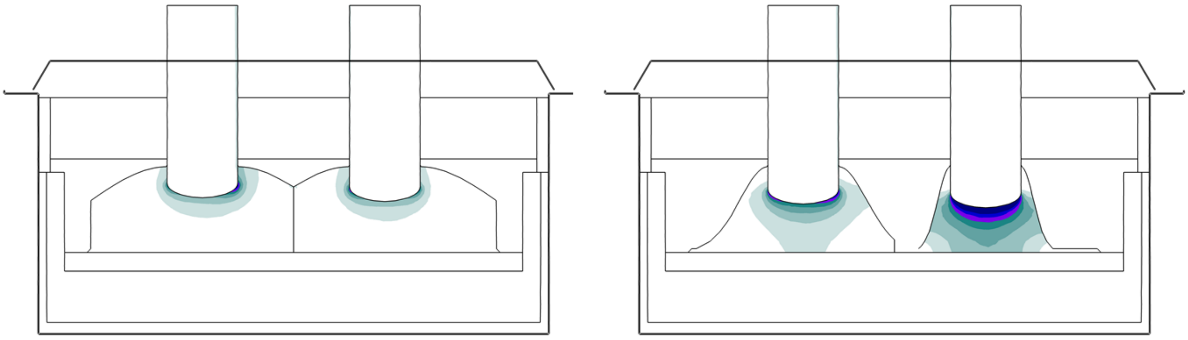

Figure 3: Models for a FeMn furnace, showing some options for the shape of the coke beds. Colors/shading below the electrode tips indicate power distribution in this region, the darker, the higher the power.

The models are very flexible and can be adapted to a wide range of geometries and distribution of material data. The geometry is parameterized to enable rapid generation of geometric alternatives for a parametric study. Although the models are adapted for Mn- and (Fe)Si processes, they can easily be adjusted for other processes.

Induced currents in steel shell

The construction steel applied in the furnace shell is magnetic and the corresponding skin depth, δ, is small compared to the thickness. Hence, induced currents will be confined to a thin surface layer. Typical current patterns for a time instant where the current enters through one electrode (in the back) and distributes to the other two (in the front) is shown in Figure 4. Behind each electrode the induced current always moves opposite to the respective electrode current. Since the currents will always form closed paths, we find three loops, with highest current concentration on the top between the electrodes. The currents are large, typically 20-30 % of the electrode currents. (Herland, Sparta, and Halvorsen, 2018).

Part of the induced currents will flow "over the top" and will be associated with a corresponding alternating magnetic field on the outside of the furnace. Case studies have shown that the magnetic field on the outside depend on inner current patterns. This indicates that appropriate measurements can supply adequate information to identify inner furnace conditions. There are three possible principles for such measurements:

- Electric field, or electric potential differences, on the steel shell
- Magnetic field just outside the steel shell
- Temperatures on the steel shell

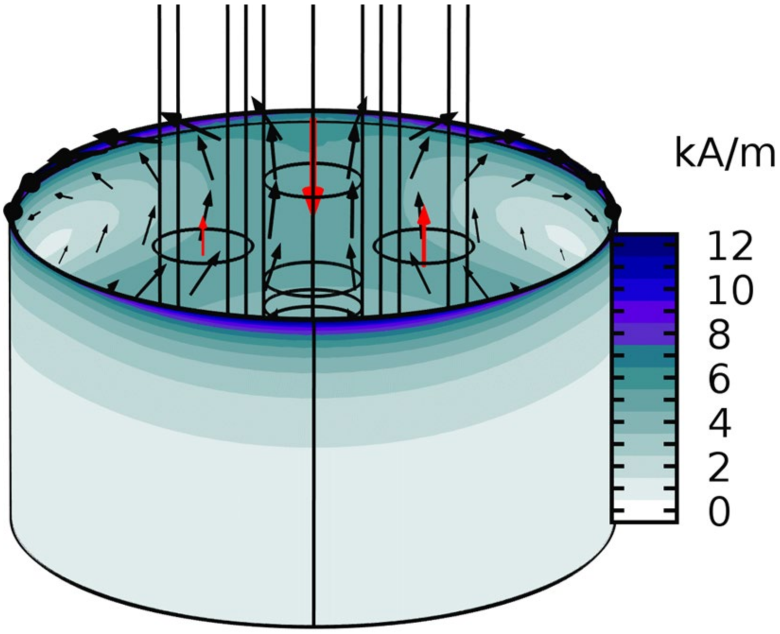

Figure 4: Typical patterns of induced currents on the inside of the steel shell. The main current enters the furnace through the back electrode and distributes to the two electrodes in the front.

The first two will conceptually measure the local magnitude of induced current on the *outside* of the steel shell (online measurements on the inside are probably not feasible), while temperatures will measure an average of the induced power on the *inside and* the *outside*. The temperatures will, of course also depend on the inner furnace temperatures and the ambient conditions. The time variation of the induced currents will, however, follow the electrode current only with a small time lag and it should be possible to separate the effect of induced currents from other effects.

METAMODELS

The ElMet project has focused on physics-based models: ranging from simple models to understand basic phenomena, to large FEM models for realistic case studies. The latter have been implemented in COMSOL Multiphysics. The drawbacks of the FEM models are that they are demanding in terms of time and computational resources, and it is not easy to see how inputs should be appropriately modified to get a desired output. This is required if a model should be applied to identify inner furnace conditions. We have therefore developed a procedure to derive metamodels from the physics-based FEM models of a furnace. Details are given in two recent publications by Sparta *et al.* (2021a and 2021b). Only a brief overview is presented in this paper.

First, we select some 12 important input parameters, including parameters to describe the inner geometry (distribution of electrical conductivity). Then we perform some hundreds of runs with the FEM model where the inputs are systematically varied according to principles of experimental design. The results are collected in a database of corresponding inputs and outputs. A statistical method, e.g., partial least square regression (PLSR), can then be applied to link inputs and outputs. (Sparta *et al.*, 2021a, Sparta *et al.*, 2021b).

A metamodel can be realized in two "directions". The "classical" or "direct" multivariate metamodel is a function from inputs to outputs. It will show how the inputs influence the output values, and what inputs are most important in this respect. In the opposite, or "inverse", direction one constructs a function/relation *from* the outputs *to* the inputs. The latter can be used for identification of inner conditions, provided the model is not "sloppy", i.e., important inner conditions are only "vaguely" defined by the inputs (more than one set of inputs will cause the same, or very similar, state of the furnace). Further research is required, but so far the methodology looks promising. (Sparta *et al.*, 2021a, Sparta *et al.*, 2021b).

It has also been shown that the standard measurements (operational data) are not sufficient to identify inner furnace conditions (Stråbø, 2020).

MATERIAL DATA, VERIFICATION

The ElMet project has concentrated on appropriate mathematical modeling of the electrical conditions, but some efforts have also been spent on material data and model verification.

Electrical and thermal conductivity – Homogenization

Effective electrical conductivity is complicated for inhomogeneous particulate materials. Our investigations have been focused on beds of carbon particles. Homogenization is a mathematical method where the average/effective quantities can be calculated based on a model of the local conditions on a small scale. This method has been adapted to electrical conductivity for particulate matter/bulk materials (Rooney, 2019).

The project has also included some studies on effective thermal conductivity where radiation is important (Kiradjiev *et al.* 2019; Rooney, Please, and Howison, 2020).

Electrical conductivity – Measurements

The studies of electrical conductivity have included measurements and experiments.

Computer tomography (CT) scans have provided a good view of the conditions within a bed of carbon particles. Each particle connects typically to other ones through 5-7 small areas ("contact points"). Such scans also show typical characteristics of the contacts. The scans can be used as a starting point to study typical current paths. But such investigation was not prioritized within the ElMet project.

Equipment for measuring effective electric conductivities in particulate matter has been developed at NTNU. The ElMet project has contributed. Measurements have been performed for carbon materials, both at room temperature and at elevated temperatures. Some results have been published by Surup *et al.* (2020).

Model verification

The ElMet project has focused on developing and testing mathematical models to understand electrical conditions in 3-phase furnaces. A comprehensive validation was outside the intention of this research project. But some limited evaluations have been carried out:

- Case studies in cooperation with the industrial partners are found to be in good agreement with furnace observations.
- Hot spots have been observed on the steel shell in regions where the simulations show high concentration of induced currents.
- Magnetic fields were measured outside the steel shell in a separate project. The general trend in these measurements agreed with ElMet simulations.

Substantially improved model validation/verification will require dedicated experiments with appropriate measurements to find the inner furnace conditions with reasonably accuracy. Another approach is to impose a change with known effects and check how well the model reproduces the expected furnace behavior. Since our project has shown that the normal operational data is not sufficient to identify inner furnace conditions (Stråbø, 2020), additional measurements are strongly recommended.

POSSIBLE FOLLOW-UP

The knowledge acquired in the ElMet project should be followed up, and improvements should be implemented industrially.

Education

Course material of relevant basics for electrical conditions (presentation and a compendium) is part of the ElMet results. This material can be reused and further developed to educate students, as well as plant metallurgists and furnace operators. The material has been made available for the industrial partners for internal use, and for education at NTNU.

Case studies

FEM models for (Fe)Si and Mn furnaces have been implemented in COMSOL Multiphysics. Models adapted for furnaces at Elkem and Eramet Norway have been handed over to the respective companies, where they have been applied for various studies. Both companies intend to apply the models for further simulations, when appropriate. The FEM models are flexible and can fairly easy be adapted to other furnaces and processes.

Combined, overall models

The ElMet model should be combined with other models for an overall view of the coupling between electrical conditions, heat flow, material flows and chemical reactions. As a start, an overall, axially symmetric model has been developed for a SiMn pilot furnace (Sparta *et al.*, 2021c). Here, DC is applied and considered to be appropriate, while AC may be required for 3D cases of full size industrial furnaces.

Measurements

The induced currents in the steel shell carry information on inner electrical conditions. Model simulations have shown that the induced currents are influenced by the inner current distribution. We recommend that the three principles for measurement are tested: electric field (potential differences), magnetic field, and temperature. We think that a lease one of these should be implemented in a future control system.

Electrode voltages can be measured by the principle proposed by Bøckman (1973). The voltages are normally measured between each electrode and the bottom of the furnace steel shell, where the latter should correspond to a “neutral point” inside the furnace. But our ElMet simulations show that there is no electrical contact between the neutral point and the outside of the steel shell for (50 Hz) *alternating currents*. The 50 Hz coupling is first between an inner neutral point and induced currents inside the steel shell, through the magnetic field. Then part of these currents flows outside the steel shell, where they influence the 50 Hz electric potential in this region.

We conclude that the conditions for the Bøckman measurement is not well understood and recommend that it is reviewed. ElMet type of simulations as well as additional measurements should be utilized. The Bøckman principle lacks sound scientific basis, but that does not necessarily imply that it cannot be used.

We also recommend that other standard electrical measurements are reviewed.

Identification of inner conditions

The ElMet project has established a foundation for future on-line identification of inner furnace conditions. This will require further challenging, multi-disciplinary research, including:

- Further adaptation and testing of ElMet models
- Further development of suitable metamodels
- Coupling electrical models to models for the process conditions
- New measurements for on-line use
- Suitable (furnace) experiments
- Proper data analysis, e.g., including novel techniques from artificial intelligence

CONCLUSIONS

The research project Electrical Conditions and their Process Interactions in High Temperature Metallurgical Reactors (ElMet) has established a sound basis for understanding electrical conditions in metallurgical processes.

The project has demonstrated that various types of mathematical models are required:

- Equation analysis and simple models to properly understand the fundamentals
- Proper overall models for realistic case studies
- Metamodels for possible on-line use and identification of inner conditions

Flexible 3D simulations models have been developed and tested for (Fe)Si- and Mn-processes. The models can fairly easy be adapted to other furnaces and processes.

An electromagnetic AC proximity effect has been discovered and studied. Currents and electromagnetic fields in parallel layers are strongly coupled. This effect will "push" currents away from good conductors, like a metal bath or the steel shell. More currents will run higher up between the electrodes for AC than predicted by DC solvers. A simple estimate has been established to check whether this effect can be important for a concrete case. The same effect enhances induction currents in a conductive (carbon) lining.

Induced currents in the furnace steel shell carry information on inner furnace conditions. Measurements are recommended, for possible implementation in future on-line control systems. Studies of such induced currents have also disclosed that the Bøckman principle for measuring electrode voltages lacks a sound scientific basis.

Proper metamodels seem to be suitable for future on-line use and to identify inner furnace conditions. Such identification will require further challenging, multi-disciplinary research.

ACKNOWLEDGEMENTS

This work is part of the research project Electrical Conditions and their Process Interactions in High Temperature Metallurgical Reactors (ElMet), Project No.: 247791; with financial support from The Research Council of Norway and the companies Elkem, and Eramet Norway. The paper is also partly funded by SFI Metal Production, Centre for Research-based Innovation, 237738, with financial support from the Research Council of Norway and the partners of SFI Metal Production.

REFERENCES

Bermúdez, A., Bullón, J., Pena F. 1998. A Finite Element Method for the Thermoelectrical Modelling of Electrodes, *Commun. Numer. Meth. Engng*, vol. 14, pp. 581-593, https://doi.org/10.1002/(SICI)1099-0887(199806)14:6<581::AID-CNM175>3.0.CO;2-S

Bermúdez, A., Gómes, D., and Salgado, P. 2014. *Mathematical Models and Numerical Simulations in Electromagnetism.* Springer International Publishing.

Bøckman, O. C. 1973. Arrangement for Measuring the Crater Voltages in a Three-Phase Electric Furnace with Electrodes Arranged in a Delta, *U.S. patent*, http://patft1.uspto.gov/netacgi/nph-Parser?patentnumber=3757021

Darmana, D., Olsen, J.E, Tang, K. and Ringdalen E. 2012. Modelling Concept for Submerged Arc Furnaces. *Ninth International Conference on CFD in the Minerals and Process Industries,* Melbourne, Australia, 10-12 December 2012, N.62.

Dhainaut, M., 2004. Simulations of the Electric Field in a Submerged Arc Furnace, *Infacon X, Tenth International Ferroalloy Congress*, Cape Town, South Africa, 1-4 February 2004, pp. 605-613.

Fromreide, M. 2021. *PhD Thesis.* University of Santiago de Compostela. To be submitted.

Fromreide, M., Gómez, D., Halvorsen, S.A. and Herland, E.V., Salgado, P. 2021a. (under consideration) Reduced 2D/1D Mathematical Models for analysing Inductive Effects in Submerged Arc Furnaces.

Fromreide, M., Halvorsen, S.A., Sparta, M., Risinggård, V.K., Salgado, P., Gómez, P., Herland, E.V. 2021b. (in press) Effects of Alternating Currents in the Hearth of Submerged Arc Furnaces, *Infacon XVI, Sixteenth International Ferroalloy Congress*, Trondheim, Norway, 26-29 September, 2021.

Halvorsen, S.A., Olsen, H.A.H. and Fromreide, M. 2016, An Efficient Simulation Method for Current and Power Distribution in 3-Phase Electrical Smelting Furnaces. *IFAC-PapersOnLine 49.20*, pp.167-172.

Herland, E.V. Sparta M. and Halvorsen S.A. 2018. 3D-models of proximity effects in large FeSi and FeMn furnaces. *J. S. Afr. Inst. Min. Metall.* vol. 118. pp. 607–18. http://dx.doi.org/10.17159/2411-9717/2018/v118n6a8

Herland E.V. Sparta M. and Halvorsen S.A. 2019. Skin and Proximity Effects in Electrodes and Furnace Shells. *Metall Mater Trans B*, vol. 50, pp.2884-2897, https://doi.org/10.1007/s11663-019-01651-8

Karalis, K.T., Karkalos, N., Cheimarios, N., Antipas, G.S.E., Xenidis, A., Boudouvis, A.G. 2016. A CFD analysis of slag properties, electrode shape and immersion depth effects on electric submerged arc furnace heating in ferronickel processing, *Appl. Math. Model.*, vol. 40, pp. 9052-9066

Karalis, K., Karalis, N., Karkalos, N., Antipas, G.S.E. and Xenidis, A. 2020. Computational fluid dynamics analysis of a three-dimensional electric submerged arc furnace operation, *preprint*, https://doi.org/10.31219/osf.io/xgnse, last accessed Jan 12, 2021

Kiradjiev, K.B. Halvorsen, S.A., Van Gorder, R.A., Howison, S.D. 2019. Maxwell-type models for the effective thermal conductivity of a porous material with radiative transfer in the voids, *Int. J. Thermal Sciences,* vol. 145 https://doi.org/10.1016/j.ijthermalsci.2019.106009

Larsen, B., Feldborg, H., Halvorsen, S.A. 2013. Minimizing thermal stress during shutdown of Søderberg electrodes, *Infacon XIII, Thirteenth International Ferroalloy Congress*, Almaty, Kazakhstan, 9-12 June, pp. 453–66

Rooney, C. 2019. *Homogenisation of the Electrothermal Behaviour of Granular Material*, DPhil Thesis, University of Oxford.

Rooney, C., Please, C.P, Howison, S.D. 2020. Homogenisation applied to thermal radiation in porous media, *Euro. J. Appl. Math.*, Published online by Cambridge University Press, https://doi.org/10.1017/S0956792520000388

Sparta, M., Varagnolo, D., Stråbø, K., Halvorsen, S.A., Herland, E.V., Martens, H. 2021a. Metamodeling of the electrical conditions in submerged arc furnaces. *Metall Mater Trans B.*, https://doi.org/10.1007/s11663-021-02089-7.

Sparta, M., Varagnolo, D., Martens, H., Halvorsen, S.A. 2021b. Metamodeling of the electrical conditions in submerged arc furnaces, *Infacon XVI, Sixteenth International Ferroalloy Congress*, Trondheim, Norway, 26-29 September, 2021.

Sparta, M., Risinggård, V.K., Einarsrud, K.E., Halvorsen, S.A. 2021c. An overall furnace model for the silicomanganese process (forthcoming).

Stråbø, K. 2020. *Metamodeling and inverse metamodeling electrical conditions in ferromanganese furnaces*, Master Thesis, Norwegian University of Science and Technology (NTNU)

Surup, G.R., Pedersen, T.A, Chaldien, A., Beukes, J.P., Tangstad, M. 2020. Electrical Resistivity of Carbonaceous Bed Material at High Temperature, *Processes*, vol. 8, https://doi.org/10.3390/pr8080933

Tesfahunegn, Y.A., Magnusson, T., Tangstad, M., and Saevarsdottir, G., 2018. Effect of electrode shape on the current distribution in submerged arc furnaces for silicon production – A modelling approach. *J. S. Afr. Inst. Min. Metall.* vol.118. pp.595-600. http://dx.doi.org/10.17159/2411-9717/2018/v118n6a6

Tesfahunegn Y.A. Magnusson T. Tangstad M. and Saevarsdottir G. 2020. Comparative Study of AC and DC Solvers Based on Current and Power Distributions in a Submerged Arc Furnace. *Metall Mater Trans B.* vol.51. pp.510-518, https://doi.org/10.1007/s11663-020-01794-z

Svenn Anton Halvorsen

Chief Scientist, NORCE Norwegian Research Centre

Svenn Anton Halvorsen has a Master's degree in Technical Physics and a PhD in Numerical Mathematics from The Norwegian University of Science and Technology (NTNU). Svenn Anton has worked for 20 years in the R&D Centre of Elkem ASA, a global metallurgical company. He then founded and successfully ran his own consultancy company for 7 years. His current position is as Chief Scientist at NORCE.

Svenn Anton has extensive theoretical and practical experience in a wide variety of mathematical models for industrial applications. Recently, he has been Project Leader for a large competence project on three-phase electrical conditions in metal processes. This project has involved strong multi-disciplinary research in cooperation with leading universities and the metallurgical companies Elkem and Eramet.