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Development and Utilization of Models for the Electrical Conditions in Submerged Arc Furnaces (SAF).

M. Sparta[1], V. K. Risinggård[1], U. Thisted[1], M. Fromreide[1]
1. NORCE Research AS, Kristiansand, Norway.

Abstract

This work addresses the critical challenge of accurately determining the inner states of three-phase electric smelting furnaces used in ferro-alloy production. In this context, we developed detailed, parametrized 3D Finite Element Method models of industrial-size Submerged Arc Furnaces (SAF) in COMSOL Multiphysics®. Our models use idealized yet realistic geometrical representations of structural elements and materials. The AC/DC Module, specifically utilizing the Magnetic and Electric Fields (mef) interface, was employed to set up the electrical conditions within the furnace. An Electrical Circuit (cir) model was integrated to track the true power for each phase, providing a comprehensive understanding of power flow.

Keywords: metal production, electrical conditions, three-phases system.

Introduction

Three-phase electric smelting furnaces are crucial for primary metal production, but optimizing their performance, energy efficiency, product quality, and environmental impact is a significant challenge. The extreme heat and harsh internal conditions make direct observation and experimental surveys nearly impossible.

Numerical modeling, specifically the Finite Element Method (FEM), has emerged as a powerful tool for analyzing these complex systems. By simulating the internal furnace environment, models can provide insights that are otherwise unattainable through physical experimentation alone. [1] This paper presents the results for a series of comprehensive computational studies utilizing a detailed FEM model of an industrial-scale SAF, developed in COMSOL 6.2. The base model provides a foundational understanding of the furnace's electromagnetic behavior, including the distribution of active and reactive power, as well as electric and magnetic fields. This serves as the basis for deriving key operational parameters such as resistances and reactances. [2, 3]

Building upon this foundational model, we have developed and applied several specialized derived models to address critical challenges in SAF operation and analysis. These specialized models have allowed us to investigate the optimal use of virtual magnetometers for improved real-time monitoring, assess the efficacy of traditional multi-lead measurement techniques designed to mitigate electromagnetic interference, and generate extensive datasets for the training of advanced surrogate models. The development of these highly parametrized models is a key step towards creating computationally efficient tools for testing and rapid prototyping.

Through the systematic application of these models, this research aims to provide invaluable insights into the complex electrical and electromagnetic phenomena within SAFs, ultimately contributing to improved operational control, enhanced measurement accuracy, and the development of more efficient and sustainable production processes.

Experimental Set Up

The general physical model is based on an industrial furnace, cf. Figure 1. It incorporates three electrodes placed in an equilateral triangle inside a circular steel shell. Inside the shell, there is a layer of non-conductive insulation, and a lining of conductive carbon materials of variable thickness. The carbon lining extends up above the alloy layer. [4]

The internal furnace environment is modeled with attention to detail. The charge banks are represented with varying electrical properties, specifically resistivity ranging from 10 to 300 mΩm. Beneath the electrodes, there are coke beds or craters, depending on the process at hand. For furnaces with coke beds, these are modeled with a varying diameter. The resistivity is set between 4.12 and 7.20 mΩm, and their shape can be controlled by a single parameter.

For furnaces with craters, special consideration was given to the representation of the electrode craters and arcs [5]. Craters are modeled as non-conductive gas domains surrounding the electrode tips. These are enveloped by a layer of carbide with increased conductivity. The arcs within the craters are treated as resistive elements, specifically as conductive cylinders with an assumed conductivity of 7000 S/m. The model distinguishes between side arcs, which connect the electrode's vertical surface to the crater wall, and a bottom arc, which is included if the electrode tip-to-molten alloy bath distance is less than 20 cm. The distribution of side arcs can be adjusted by a parameter to favor either the center or periphery of the furnace. It is important to note that structural elements surrounding the furnace are not included in this model, simplifying the domain to focus on the electromagnetic behavior within the furnace and its immediate surroundings.

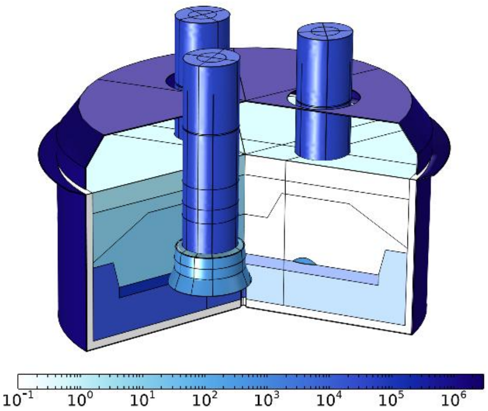


Figure 1. Schematic representation of the model. The electrical conductivity of the material is shown on a logarithmic color scale in S/m.

Numerical Model

The simulation utilizes COMSOL® Magnetic and Electric Fields interface to solve Maxwell's equations. This was achieved by employing the magnetic vector potential and a scalar electric potential formulation, with the equations discretized using quadratic finite elements to ensure high-fidelity spatial resolution. The model is also coupled with an external electrical circuit model, which acts as the power supply and tracks the true power for each of the three phases. [6]

Simulation Results

This section presents three case studies for which the base model has been adapted to focus on specific knowledge gaps.

Virtual magnetometers.

The furnace models can predict the magnetic field at any point in space, a capability that is crucial for optimizing data collection. By studying the pattern of the magnetic field, we can support the development of novel methods for real-time measurements. For example, Figure 2 shows the projection of a cylindrical probe surface into a 2D map of the tangential, radial and vertical components of the magnetic field. This visualization could facilitate the identification of optimal strategies for acquiring the most comprehensive and informative data concerning the furnace's internal condition.

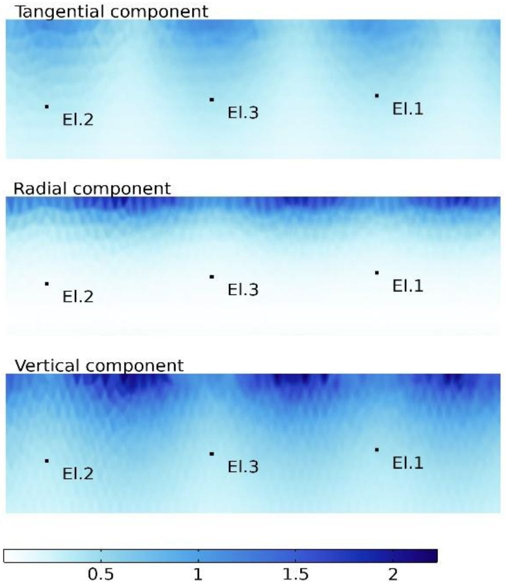


Figure 2. Projection of a cylindrical probe surface into a 2D map of the tangential, radial and vertical components of the magnetic field (mT) around the furnace. The points on the probe surface closer to the tip of the electrodes are marked.

Assessment of Traditional Multi-Lead Measurement Methods.

To improve the accuracy of core voltage measurements in smelting furnaces, a common technique is the Bøckman system. This method involves dividing the measuring lead into three symmetrically arranged parts around the furnace. The goal is to use destructive interference to cancel out voltages induced by the strong magnetic fields present in the furnace environment. [7]

Using our models, we conducted a rigorous analysis of this and similar multi-lead measurement methods. Our simulations allowed us to examine in detail the effectiveness and limitations of these compensation techniques across a variety of operating conditions. This provided a deeper understanding of how well these methods perform in practice and where their limitations lie.

These results as exemplified in Figure 3 where the investigation of an asymmetry in the placement of the leads reveal the shortcomings of the destructive interference of the induced voltages. The system can however be compensated by opportune calibration.

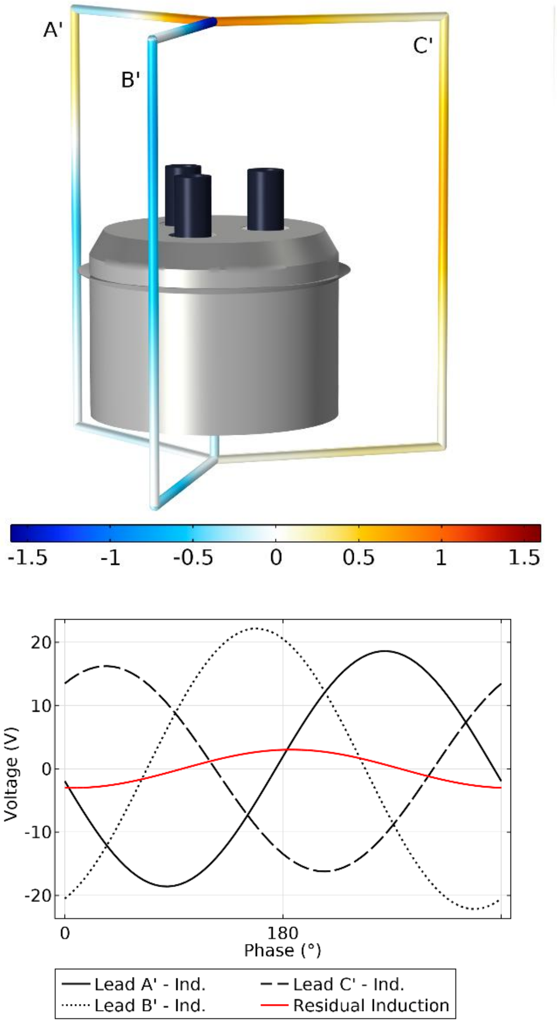
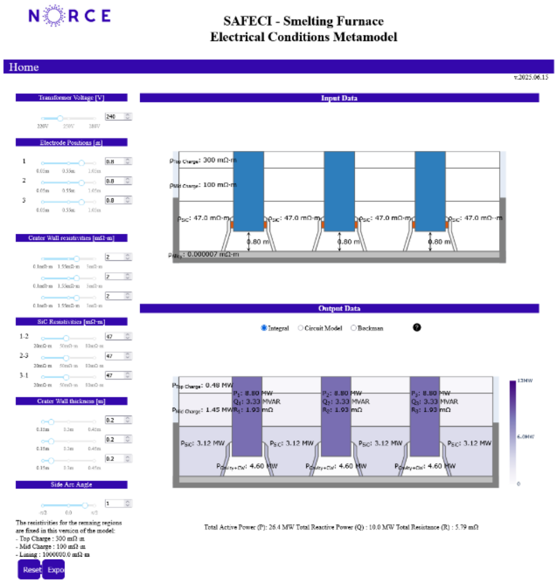


Figure 3. Top: Asymmetry in the placement of the leads color coded with the instantaneous amplitude of the tangential electric field (V/m). Bottom: Induction in the leads and effect on the partial destructive interference (red).

Surrogate Model Training.
By leveraging a highly parametrized version of our furnace model, we can efficiently generate large, diverse datasets. This data is the foundation for training advanced surrogate models (also known as metamodels or reduced-order models). These models enable rapid, computationally inexpensive predictions of furnace behavior for a wide range of input variables, eliminating the need for time-consuming, full-scale simulations. We use these surrogate models as the core engine for web interfaces, allowing users to quickly and accurately predict the furnace's response to various conditions. [8] [9] [10]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SAFECI - Smelting Furnace
Electrical Conditions Metamodel

Home

v.2025.06.15

Transformer Voltage [V]: 240

Electrode Positions [m]
1: 0.8
2: 0.8
3: 0.8

Crater Wall resistivities [mΩ·m]: 2, 2, 2

SiC Resistivities [mΩ·m]
1-2: 47
2-3: 47
3-1: 47

Crater Wall thickness [m]: 0.2, 0.2, 0.2

Side Arc Angle: 1

The resistivities for the remaing regions are fixed in this version of the model:
- Top Charge : 300 mΩ·m
- Mid Charge : 100 mΩ·m
- Lining : 1000000.0 mΩ·m

Input Data

Output Data

● Integral ○ Circuit Model ○ Backman

Total Active Power (P): 26.4 MW Total Reactive Power (Q) : 10.0 MW Total Resistance (R) : 5.79 mΩ

Figure 4. A web-based simulator for the electrical conditions in submerged arc furnaces is available at https://safeci.web.norce.cloud/

Conclusions

This work provides a significant advancement in understanding the complex internal states of three-phase electric smelting furnaces. Given the challenges of direct measurement within the harsh furnace environment, we developed a sophisticated COMSOL® model of an industrial-size submerged arc furnace. The model, which incorporates realistic geometric representations and material properties, uses the AC/DC Module and the Magnetic and Electric Fields interface to accurately simulate the furnace's electrical conditions. We also integrated an Electrical Circuit model to precisely control and track the true power for each phase.

Our foundational model provides critical insights into power distribution (active and reactive), as well as the electric and magnetic fields throughout the furnace. Building on this, we developed a series of specialized models to address specific operational challenges. We have investigated virtual magnetometers, this could provide a pathway for more effective real-time monitoring and control. We also rigorously assessed traditional multi-lead measurement methods, analyzing their effectiveness and limitations in mitigating magnetically induced errors. Finally, by creating highly parametrized versions of our model, we generated diverse datasets to train advanced surrogate models. These models enable rapid, computationally inexpensive predictions of furnace behavior, eliminating the need for time-consuming full-scale simulations.

In summary, this research offers valuable insights into the complex electrical and electromagnetic phenomena within SAFs. The systematic application of these FEM models contributes directly to improved operational control, enhanced measurement accuracy, and the development of more efficient and sustainable production processes for ferro-alloys.

References

[1] S. A. Halvorsen, M. Sparta, V. K. Risinggård and M. Fromreide, "Electrical Conditions in 3-phase Submerged Arc Furnaces: Learning from the ElMet Project," in *Proceedings of the 16th International Ferro-Alloys Congress (INFACON XVI)*, Trondheim, 2021.

[2] E. V. Herland, M. Sparta and S. A. Halvorsen, "3D models of proximity effects in large FeSi and FeMn furnaces," *Journal of the Southern African Institute of Mining and Metallurgy,* vol. 118, p. 607–618, 2018.

[3] E. V. Herland, M. Sparta and S. A. Halvorsen, "Skin and Proximity Effects in Electrodes and Furnace Shells," *Metallurgical and Materials Transactions B,* vol. 50B, pp. 2884-2897, 2019.

[4] M. Fromreide, D. Gómez, S. A. Halvorsen and P. Salgado, "Induced Currents in the Lining and Steel Shell of Submerged Arc Furnaces," *Journal of Sustainable Metallurgy* , vol. 9, pp. 375-385, 2023.

[5] V. K. Risinggård, M. Sparta, M. Fromreide and S. A. Halvorsen, "Large Electrode Movements: Realistic Electrical Crater Models," in *Proceedings of the Silicon for the Chemical & Solar Industry XVI*, 2022.

[6] I. Monsen, "Circuit Modelling of Submerged Arc Furnaces and Their Power Supply Systems," Master Thesis-University of Oslo, 2025.

[7] M. Sparta, V. K. Risinggård and U. Thisted, "Bockman method for measuring furnace core voltages: a modelling review," *Proceedings of the Silicon for the Chemical and Solar Industry XVII,* pp. 1-10, 2024.

[8] M. Sparta, D. Varagnolo, K. Stråbø, S. A. Halvorsen, H. E. V. and H. A. Martens, "Metamodeling of the Electrical Conditions in Submerged Arc Furnaces," *Metallurgical and Materials Transactions B,* vol. 52B, pp. 1267 - 1278 , 2021.

[9] M. Sparta, M. Fromreide, V. K. Risinggård and S. A. Halvorsen, "Electrical Conditions in Submerged Arc Furnaces: A Web-Based Simulator," in *Proceedings of the Silicon for the Chemical & Solar Industry XVI* , 2022.

[10] M. Sparta, M. Fromreide, E. Nordgård-Hansen and V. K. Risinggård, "Electrical conditions in a manganese submerged arc furnace: a web-based simulator," in *Proceeding of International Ferroalloys Congress INFACON XVII*, Beijing, 2024.

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