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An Efficient Simulation Method for Current and Power distribution in 3-Phase Electrical Smelting Furnaces *

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Abstract: A simplified simulation method for 3-phase AC smelting furnaces is presented and analyzed. The DC potential equation is first solved for three basis problems where the potential is 1 V at the top of one electrode and 0 V at the two others. Then these three solutions are combined, taking the phase shift between the electrodes into account. The method ignores electromagnetic induction. Mathematical analysis shows that this approximation is better the smaller the furnace. Further studies are required to find how well it performs for large furnaces. The method has been tested using COMSOL Multiphysics. Computed results are compared with a pure DC approach. The method is suitable to provide more understanding of AC effects in 3-phase furnaces. When simulation results are compared with full AC computations, effects of the phase shift between the electrodes can be separated from effects due to electromagnetic induction.

Keywords: Simulation method, three-phase AC, DC approximation, submerged arc furnace, power distribution, current distribution.

1. 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. One identified knowledge gap is an accurate understanding of the effects of 3-phase alternating current, including how the associated power distribution governs the chemical reactions and temperature distribution. An efficient method for computing 3-phase current paths and power distribution is a required step to close this knowledge gap.

1.1 DC Simulations

Among early simulations, we find Dilawary and Szekely (1977 and 1978). They focus on heat transfer and fluid flow in an axially symmetric geometry. Maxwell's equations are the basis for the electromagnetic part of the problem. Dilawary and Szekely performed an analysis for the AC problem, but the simulations are based on DC to avoid too complex computations.

Sheng et.al. (1998) studied a full 3D problem for electric smelting of nickel matte. The electromagnetic problem was simplified by applying an "equivalent direct current" instead of solving for the AC problem.

Dhainaut (2004) performed electrical 3D simulations for a typical submerged arc furnace for the production of high carbon ferromanganese. The simulated furnace runs on 3-phase AC. Instead of performing full AC simulations, Dhainaut has solved the DC equations and chosen "only one instant of time where one electrode has a voltage of 100 V while the two others have a voltage of -50 V".

These previous publications do not clarify when/whether DC simulations are an appropriate approximation for industrial 3-phase furnaces.

1.2 Full AC Simulations

A few decades ago, full 3D simulations for 3-phase furnaces would require prohibitively expensive computer resources, and proper software were not readily available. Today, the theory is well established (see for instance, Bermúdez et.al. 2014) and commercial software like COMSOL Multiphysics and ANSYS offers full AC simulations on affordable workstations.

Such computations are, however, still complex and lengthy.

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1.3 AC low frequency approximation

In this paper, we will present a third alternative, utilizing a low frequency approximation for Maxwell's equations. The computational complexity will then be similar to the DC approximation and much simpler than full AC.

2. THEORY

2.1 Maxwell's equations – Electric field, regimes, skin effect, DC approximation

The electrical computations are based on Maxwell's equations for electrically conducting media. We now assume constant parameters, harmonic time variation, and apply Ohm's law. The equation for the electric field can then be written as (see, for instance, Schlanbusch et.al., 2014):

$$\nabla^2 \vec{E} = i\omega\sigma_e\mu\vec{E} - \frac{\omega^2}{c^2}\vec{E}\,; \qquad (1)$$

where $\vec{E}$ is the electric field vector, i is the imaginary unit, ω is the angular frequency, σ_e is the electrical conductivity, μ is the magnetic permeability, and c is the speed of light.

A similar equation can be derived for the magnetic field.

Equation (1) is non-dimensionalized by introducing the tilde-variables $x = L\tilde{x}$, $y = L\tilde{y}$, $z = L\tilde{z}$, and $\vec{E} = E_0\vec{\tilde{E}}$; where L is a characteristic length scale and E_0 is a characteristic field strength. The non-dimensional equation can be written as:

$$\tilde{\nabla}^2\vec{\tilde{E}} - 2i\left(\frac{L}{\delta}\right)^2\vec{\tilde{E}} + \left(2\pi\frac{L}{\lambda}\right)^2\vec{\tilde{E}} = 0\,; \qquad (2)$$

where $\tilde{\nabla}^2$ is the non-dimensional Laplacian, δ is the skin depth defined by:

$$\delta = \sqrt{\frac{2}{\omega\sigma_e\mu}}\,, \qquad (3)$$

and λ is the wavelength given by:

$$\lambda = \frac{2\pi c}{\omega}. \qquad (4)$$

If $(2\pi L/\lambda)^2$ is sufficiently small, the last term in equation (2) can be neglected, and if $(L/\delta)^2$ is small, then the second term can also be dropped. Hence, there will be different regimes for the electric field depending on the scale parameter, L:

- Electromagnetic waves, $\lambda << L$
- Alternating current (AC), $\lambda >> L$
    - High frequency, $\delta << L$
    - Low frequency, $\delta \approx L$
- Direct current (DC), $\delta >> L$.

For electrical smelting furnaces, $\lambda >> L$, electromagnetic waves can safely be neglected and the third term in equation (2) can be dropped.

2.2 Simplified AC – Low frequency/DC approximation

For sufficiently low frequency, the skin depth, δ, will be large compared to L, and the second term in equation (2) will be correspondingly small. Then we are left with only one significant term in equations (2) and (1), i.e. the DC approximation for the E-field equation.

Applying the DC-approximation for an alternating current means that:

- The electrical conditions at any instant of time can be found by solving the DC problem.
- Currents and voltages are properly described by their effective (RMS) values.

One main effect of AC is that the electromagnetic fields (and electric currents) do not penetrate deeply into a conductive media, but are confined to a region (skin) near the surface. For a thick conductor, $\delta << L$, the field strengths decay as $\exp(-x/\delta)$, where x is the distanced from the surface.

Strictly speaking, the DC approximation requires $\delta >> L$. For industrial applications, this is clearly fulfilled if $\delta > 4.5L$, since the numerical factor in equation (2), $2(L/\delta)^2$, then will be less than 1/10. In many cases, the DC approximation will be reasonable for lower values of the skin depth, even into the low frequency region. Consider, for instance, current in an insulated cylindrical conductor. The DC approximation gives constant current distribution in the cylinder, while AC deviates only slightly when $\delta/R > 1$, where R is the radius of the conductor, see e.g. Schlanbusch et.al. (2014).

Table 1 shows typical skin depths for a large high carbon ferromanganese (HC FeMn) furnace operating with a frequency of 50 Hz, where the furnace zones and electrical conductivities are according to Dhainaut (2004). The conductivity for Søderberg electrodes seems somewhat high. The table was therefore supplemented. Halvorsen et.al. (1999) presents a table of "constructed data for Søderberg paste", i.e. their data are reasonable, but not necessarily true. We have applied their data at some 2000 °C.

Table 1. Skin depths – HC FeMn furnace, 50 Hz AC

Furnace zones and conductivities according to Dhainaut (2004)
Electrodes[1)] according to Halvorsen et.al. (1999)

Furnace zone	El. conductivity [S/m]	Skin depth [m]
Mixture, 400 °C	0.075	260
Mixture, 800 °C	0.15	184
Mixture, 1200 °C	15	18.4
Coke beds,1500 °C	150	5.81
Electrodes	150 000	0.184
Electrodes[1)]	35 000	0.380
Metal bath	150 000	0.184