# MODELING OF POWER AND HEAT LOSSES OF ELECTRICAL ARC FURNACES

**Eder Trejo[1], Fernando Martell[2*], Alejandro Montesinos[1], Osvaldo Micheloud[2]**

[1]Instituto Tecnológico y de Estudios Superiores de Monterrey, School of Engineering and Information Technologies, 64000 Monterrey, N.L., Ave. Eugenio Garza Sada 2501, México.
[1]Chemical Engineering Department, [2]Computer and Electrical Engineering Department

**a00158688@itesm.mx (Fernando Martell)*

**Abstract**

Two simplified equations to calculate electrical and cooling water losses of a conventional Electrical Arc Furnace (EAF) are proposed. These equations were obtained by modeling electrical and heat transfer aspects of the EAF in order to determine some of the EAF losses. Fundamental aspects of the electrical power delivery and heat transfer theory were considered to propose an equation for the EAF power system electrical losses to compute the amount of active power in the arc including harmonic distortion effects. In addition, a correlation of thermal losses in function of slag coating thickness on water-cooled panels is presented. The electrical model was used to define the boundary conditions of the fluid dynamics simulation to obtain the heat transfer by convection and radiation of the arc to calculate the thermal losses and complete the EAF energy balance. The proposed heat energy balance also considers another fuels supplies and exothermic chemical reactions inside the EAF. The intention of this research work is to serve as framework for further research oriented to improve both the electrical and thermal energy efficiencies of the EAF and contribute in this way to increase the productivity in steel plants and as well as to reduce energy consumption.

**Keywords: Electrical Arc Furnace, Harmonic Distortion, Heat Loss, Energy Efficiency.**

**Presenting Author's biography**

Eder Trejo finished his carrier of Chemical Engineering and cursed a Master Degree in Energetic Engineering at the Tecnológico de Monterrey (ITESM) in Monterrey, México. Eder is student of the Engineering Sciences PhD Program and member of the Roberto Rocca´s Energy Cathedra which is supported by Techint Group (Ternium and Tenaris Mexican Steel Plants).

## 1. Introduction

Electrical Energy is the main energy source for steelmaking plants equipped with electrical arc furnaces (EAFs) for scrap fusion and metallurgical refining. EAF facilities are relevant to study because they contribute to a great proportion (estimated to be 34% in 2010) of the world´s steel, production. EAFs are thermo-processing units using plasma arcs as source of heat capable of melting scrap or direct reduced iron (DRI) trough the heat transfer phenomena of convection and radiation. The plasma arc is generated by a high power system connected to graphite electrodes that reaches the scrap and other materials inside the furnace to strike an electrical arc. This heat source is combined with the more intensive use of chemical energy trough natural gas burners and carbon-oxygen lances [1].

This research work proposes a model to calculate the power (electrical) and heat (thermal) losses of a conventional EAF. The model considers fundamental aspects of the electrical and heat transfer theory. It is novel because proposes a formulation for the EAF power system electrical losses and computes the amount of active power in the arc including harmonic distortion effects. The energy computed from the arc is then used to calculate the boundary conditions of the arc for the computational fluid dynamics simulation (CFD) to obtain the heat convection and radiation of the arc in order to calculate the heat transfer and thermal losses and complete the EAF energy balance. The results were obtained by modeling electrical and heat transfer aspects of the EAF in order to determine some of the EAF losses for an Energy Demand statistical model reported in literature. The proposed heat energy balance also considers another fuels supplies like Natural Gas and Carbon-Oxygen trough burner and lances as well as the energy from exothermic chemical reactions inside the EAF.

## 2. Energy Balance and Efficiency

### 2.1 EAF Energy Balance

Energy balances give a general quantitative idea of electrical arc furnace as a “thermoenergetical” unit, in EAFs the specifics of electrical units are combined with those of thermo-technical ones [2]. The energy balance in an EAF follows the definition of Eq. (1) that integrates the electric power with the heat flow (wall and roof cooling), the enthalpy of the mass flow (steel, slag, off gas) and the metallurgical oxidation reactions [3].

$$\sum_{i=1}^{n} \int_{heat} \left( \dot{Q}_I + P + \dot{H}_i + \dot{R}_i \right) d\tau = 0 \qquad (1)$$

It is possible to employ reported data from statistical models to calculate the electrical demand input for a typical EAF, this model was originally by Khöle [4] and improved by others authors like Pfeifer [3], and serves to calculate the electrical input required to melt the amount of metallic and non-metallic materials loaded into the typical EAF furnace, this model also helps to calculate the chemical energy from the added fuels and from the exothermic chemical reactions, Eq.(2).

$$\frac{W_R}{kWh/t} = 375 + \left[ \frac{G_E}{G_A} - 1 \right] + 80\frac{G_{DRI/HBI}}{G_A} - 50\frac{G_{Shr}}{G_A}$$

$$-350\frac{G_{HM}}{G_A} + 1000\frac{G_Z}{G_A} + 0.3\left[ \frac{T_A}{°C} - 1600 \right]$$

$$+\frac{t_S + t_N}{\min} - 8\frac{M_G}{m^3/t} - 4.3\frac{M_L}{m^3/t} - 2.8\frac{M_N}{m^3/t}$$

$$+NV\frac{W_V - W_{Vm}}{kWh/t} \qquad (2)$$

As we can analyze in Eq. 2, the energy demand can be calculated by furnace data, however in this model is not clearly showed the way to account for the furnace energy losses what it is still needed because when realizing energy balances it is very critical to account for both electrical and thermal losses to better balance energy inputs and outputs.

### 2.2. EAF Efficiency

In EAF plants only parts of the supplied energy can be transferred into heat in the work piece because of the existing power losses, The conversion from electric energy into thermal energy is described by the efficiency [1], as indicated in Eq. (3).

$$\eta_{EAF} = \eta_e \cdot \eta_{th} = \left( \frac{Q_{th}}{W_e} \right) \left( \frac{Q_{steel}}{W_{th}} \right) = \frac{Q_{steel}}{W_e} \qquad (3)$$

Some furnaces have heat recovery units, this kind of furnaces are not considered in this study and for simplicity we assume there are two main components for the furnace efficiency the electrical and the thermal losses.

## 3. EAF Arc Power Delivery

### 3.1. Arc Electrical Circuit

When realizing power system analysis of Alternate Current EAFs it is possible to find analytical solutions for the power transfer and the electrical efficiency. The maximum electrical power to heat conversion occurs for a particular length of electric arc that is not the maximum power available at the secondary side of the transformer [2], this clearly states that there is an operational point in voltage and current for each transformer tap where the arc power reaches its peak value , the power controller operates the Arc Voltage and Arc Current up to the maximum EAF operational power to maximize production but this maximum power level is not the (efficiency wise) Arc operational power as indicated in Fig. 1, [2].

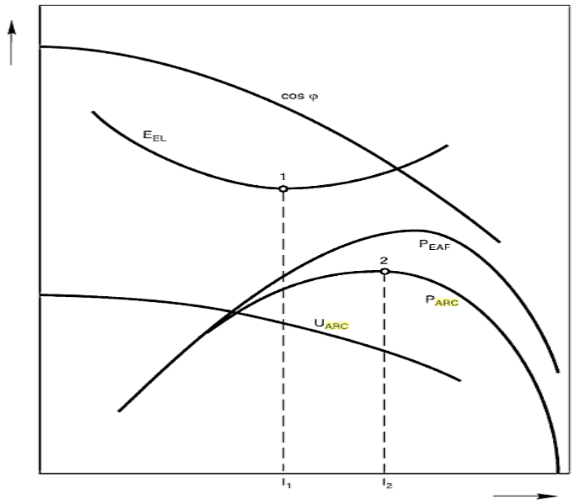


Fig. 1 EAF and ARC Power Curves, Source: Innovation in Electric Arc Furnaces [2]

The arc voltage is not sinusoidal and have harmonic distortion and because the Arc Physics imposes that the arc current is in phase with the arc current As shown in Fig. 2, therefore the arc current have harmonic distortion as well, both voltage and current Total Harmonic Distortion (THD) can be measured using conventional Fourier Analysis.

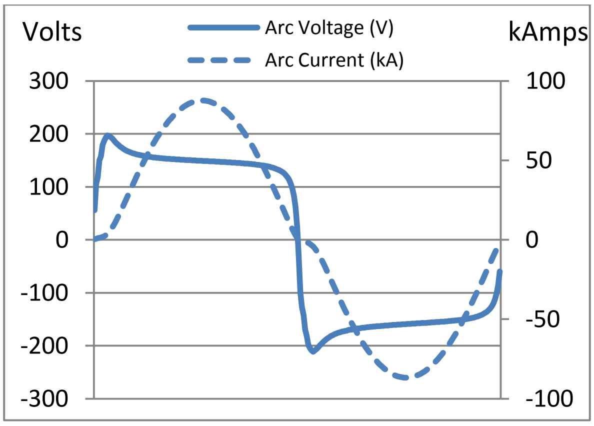


Fig. 2 Arc Voltage and Current waveforms

The harmonic currents are produced when the harmonic voltages from the arc are impressed across the electrode and furnace transformer impedances and these harmonic currents are injected back into the system [6]. The single phase circuit of an AC furnace can be modeled with a power supply in parallel to the variable arc resistance as indicated in Fig. 3. The harmonic voltage source in parallel contains the arc frequencies higher than the fundamental [5].

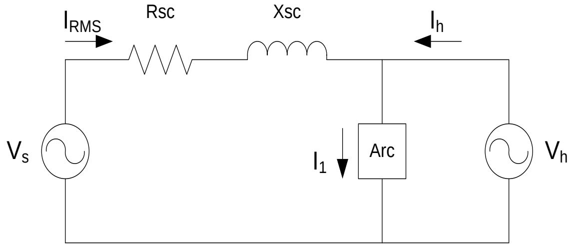


Fig. 3 EAF single phase model

DC furnaces are electrical circuits with several transformers and with typical 12 pulses power rectifiers to convert AC to DC, modeling of DC furnaces requires also the modeling of the power converter.

### 3.2. Electrical Power to Heat Conversion

In regards thermal efficiency is more complex to determine analytically, there are very interesting studies using computational fluid dynamics (CFD) modeling and simulation that calculates the power delivery by the EAF plasma arc into convection and radiation heat transport phenomena from Direct Current (DC) arcs [6] and channel arc modeling for the Alternate Current (AC) arcs [7], some important results of these models indicates the contribution of the heat transfers mechanisms of convection, radiation and electronics flows.

According to Bowman, the arc can be represented as a cylinder (conducting channel) which diameter can be estimated for an assumed radial profile and voltage gradient. The radius of the conducting channel represents the region were the temperature has dropped to ~4,600 K. Bowman proposed an expression to relate the specific conductivity with the temperature distribution in the arc channel, Eq. 4.

$$\sigma = \left[\frac{T}{940\ K} - 5.2 + 2.1 e^{\frac{T - 3{,}000\ K}{1{,}300\ K}}\right] kS/m, \quad (4)$$

In which T is the temperature. This equation applies for a concentration of 10% iron in the plasma. The average error is ~2% over the temperature range 5,000 to 14,000 K. Bowman considered a flat-toped power law to represent the temperature distribution in the arc channel (Eq. 5).

$$T = T_0 \left[1 - \left(\frac{r}{r_c}\right)^n\right] \quad (5)$$

$T_0$ is the axial temperatura and $r_c$ is the radius of the conducting channel. The current passing for the channel is given by Eq. 6.

$$I = 2\pi \int_0^{r_c} r\sigma E dr, \quad (6)$$

In which $\sigma$ is the specific conductivity and $E$ the voltage gradient. For $E$ = 9 V/cm, with $T_0$ = 10,000 K and $n$ = 2 a radius of 10 cm is obtained for a current of 101 kA which is a characteristic value in EAFs. Bowman reported nominal secondary voltage in arc furnaces values of 550 V with a voltage gradient of 9V/cm. According to this result the arc length is 60 cm.

# 4. Proposed Modeling and Simulation

## 4.1 Modeling and Calculation of Power Losses

Even that the Electrical Arc is a non-linear load the modeling of electrical losses can be approximated by resolving some superposed circuit calculations to consider the power dissipated in the resistive elements shown in Fig. 4. Power losses can be estimated considering the resistive part of the secondary short circuit impedance ($R_{SC}$) and taking the calculated arc resistance ($R_{ARC}$). The harmonic distortion losses can be calculated from the electrode current total harmonic distortion ($I_h$).

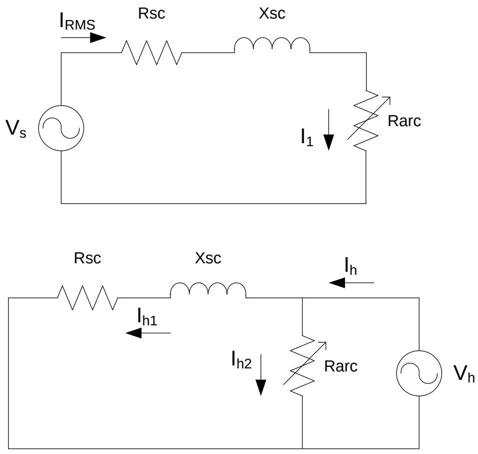


Fig. 4 Superposition of the EAF single phase model

The electrical analysis by superposition components proposed is simple and allows the calculation of the power present at the Arc Eq. (7)

$$P_{ARC} = \left[ I_1 + I_h \left( \frac{R_{SC}}{R_{SC} + R_{ARC}} \right) \right]^2 R_{ARC} \quad (7)$$

The power (electrical) losses are proposed to be calculated as in Eq. (8)

$$P_{LOSS} = \left[ I_1 + I_h \left( \frac{R_{ARC}}{R_{SC} + R_{ARC}} \right) \right]^2 R_{SC} \quad (8)$$

Therefore we can calculate the efficiency Eq. (9)

$$\eta_{el} = \frac{P_{ARC}}{P_{ARC} + P_{LOSS}} \quad (9)$$

Since $R_{ARC} >> R_{SC}$ and $I_h = THD_i$

$$\eta_e = \frac{I_1^2 R_{ARC}}{I_1^2 R_{ARC} + \left(I_1^2 + THD_i^2\right) R_{SC}} \quad (10)$$

We can approximate the electrical efficiency:

$$\eta_e = \frac{1}{1 + \frac{R_{SC}}{R_{ARC}} \left(1 + THD_i^2\right)} \quad (11)$$

On Eq. (11) the efficiency increases with the arc resistance what occurs when operating longer arcs but at the same time the efficiency is affected by the current harmonic distortion, to reduce the harmonic distortion the displacement power factor needs to be lower, so it is clearly a trade-off between the displacement power factor and the distortion power factor but there is an optimal operational point that is defined in arc length and controlled by the arc resistance.

Of course this result is an approximation and a more robust power theory under non-sinusoidal conditions is needed to better modeling the electrical efficiency in electrical arc furnaces. The proposed model is programmed in MATLAB and it performs the power system analysis to process the electrical parameters of voltage and current and based on a Fast Fourier Transform to calculate the current THD in order to calculate the arc active power. This Eq. (8) using average heat values for the electrical parameters calculates values ranging from 0.1 to 0.05 that matches with the 6 to 9% of electrical losses as reported in literature [2].

## 4.2 Simulation of Thermal Losses

According to Alexis [7] the main heat transfer to the steel is by convection and the heat losses can be attributed to the arc radiation, which we have learned that is reduced when slag covers the water-cooled panels and acts as an insulator, according to this a correlation to relate slag coating thickness the heat losses were obtained by modeling heat transfer phenomena inside the EAF. It was convenient to propose a CFD simulation to calculate the heat losses because the Heat thermal losses require the solution of heat fluxes in a non conventional geometry what only is possible using simulation software. Arc thermal losses reported in literature account for an average efficiency of about 0.75 but ranges from 0.6 to 0.8 [2].

The dimensions and temperature of the arc channel were based on electrical parameters (AC to DC equivalent average arc length and current) and used as boundary conditions to simulate the steady state thermal losses in the EAF. Different thicknesses of coating slag covering the water-cooled panels were used in the simulation to analyze its effect on thermal losses. The EAF modeled works in Direct Current and has a nominal capacity of 155 ton, it is constructed with magnetite brick whit conductivity of 3.8 W/m K in the bottom and water cooled panel in the walls and roof. A 3D geometry of the furnace was drawn to calculate the conduction, convection and radiation heat transfer Fig. 5.

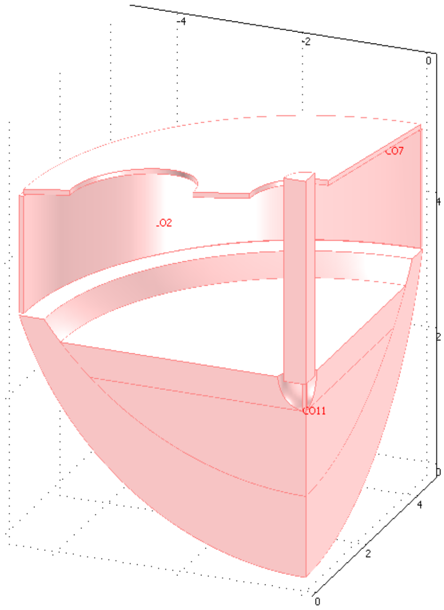

Fig. 5 Geometry used to calculate the heat transfer phenomena inside EAF.

To simulate convection inside the EAF a convection coefficient of 3.8 W/m K proposed by Bowman was used. Emmisivities of slag, roof and walls were taken has 0.7. Navier Sokes equations were solved for the water-cooled panels and coupled with the hat transfer equations to obtain the temperature variation of water and validate it with plant measurements. A Matlab algorithm was programmed to estimate the energy balance considering composition of different iron sources, electrical and chemical energy inputs and energy losses which electrical and cooling water parts were evaluated with the relations proposed in the present work. Chemical energy is calculated using total enthalpies.

### 4.3 Modelation and Simulation Results

The Matlab algorithm also processes the typical operational parameters of the furnace and calculates the distribution of energy entering and leaving the system. The energies entering to the EAF are electrical and chemical; the electrical energy demand can be calculated with the statistical model considering the electrical losses by integrating Eq. (5). The heat losses are calculated with a COMSOL Multiphysics simulation in a 3D dominium. Geometry, building materials and configuration of the furnace can be modified in the simulation to fit with the furnace that is being analyzed (Fig. 6). All the process variables, additions and consumptions are typical EAF data collected from the furnace information and control systems.

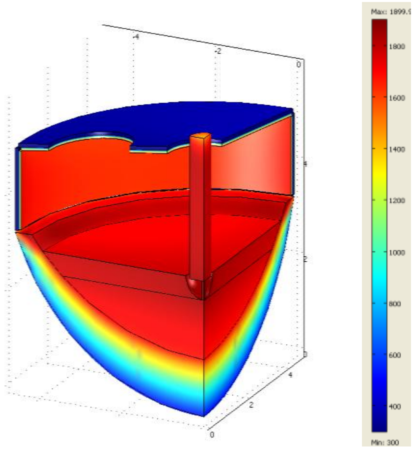

Fig. 6 Temperature distribution in the EAF indicated by colors.

Multiple simulations with different slag coating thickness were studied. The results showed a big influence of slag thickness that can be explained by the fact that slag acts as a insulator rising the internal temperature of the furnace walls and roof, consequently energy lost by radiation decreases because of lower temperature difference between walls and liquid bath. Energy losses of cooling water for different slag thickness are shown in Table 1.

Table 1: Energy losses whit different slag coating thickness.

| Slag thickness (cm) | Internal temperature of panels (K) | Energy loses (kWh) |
|---|---|---|
| 10 | 1735 | 65.6 |
| 8 | 1665 | 78.8 |
| 6 | 1587 | 96.8 |
| 4 | 1441 | 124.7 |
| 2 | 1106 | 166.1 |
| 0 | 352 | 200.6 |

When slag thickness is not available the internal temperature of the furnace can be measured, this temperature is dependent on slag thickness and can be correlated with it.

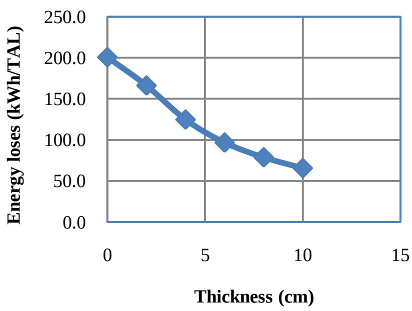


Fig. 7 Energy losses versus slag coating thickness

Energy losses are inversely proportional to slag thickness, and shown a quadratic behavior as seen in the Fig. 7. According to the results of the simulation an expression to estimate the energy losses by cooling water in the EAF is proposed:

$$E_{cw} = 202.9 - 22.74\, y + 0.895 y^2 \qquad (12)$$

Where $E_{cw}$ represents the energy losses by cooling water and $y$ is the thickness of slag coating and along with the equation (Eq. 13) for electrical losses that is calculated with the average electrical efficiency allows the calculation of two EAF losses leaving the remainder losses to be mainly the off gas losses and others small losses.

$$E_{el} = (1 - n_e)\, heat_{kWh} \qquad (13)$$

To compute the entire energy balance the chemical energy is divided in three: energy used in the furnace, energy of post combustion and energy of the heated gases (Chemical 1, 2 & 3 Energies). Energy leaving the EAF is distributed in the following components: liquid steel, slag, refrigeration water, heat losses (conduction, convection and radiation of the furnace) and off gases. A typical energy distribution of the EAF studied is shown in Figure 8.

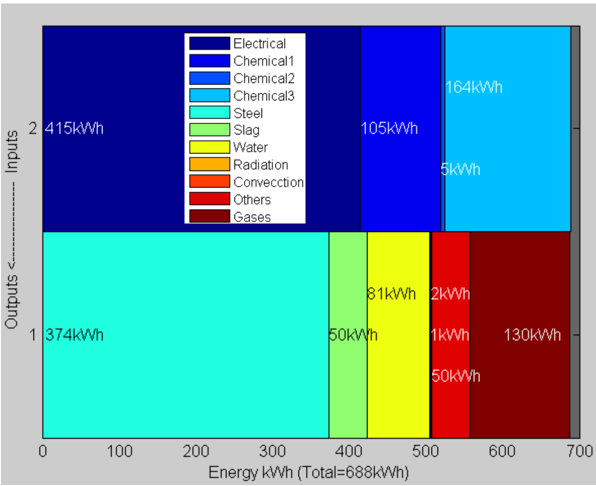


Fig. 8 Energy balance for an DC EAF without off gas heat recovery

The program developed compares the distribution results with a statistical model based in real data of hundreds of real furnaces and make a diagnostic of the energy efficiency to identify potential savings.

## 5. Conclusions

Arc power calculation and arc power losses are proposed based on EAF input electrical parameters to determine the electrical efficiency and therefore to estimate the heat transfer by convection and radiation within the plasma arc. Average arc voltages and arc currents are used to estimate arc length and arc radius to be used as boundary conditions and inputs to a Computational Fluid Dynamics simulation. The results are correlated to slag coating thickness to estimate thermal losses and complete the EAF energy balance. All materials additions, like scraps, ferrous materials and alloys as well other forms of fuel like oxy-gas from burners and oxy-carbon from lances are used to calculate the mass and energy balances. This modeling and simulation could server to determine operational points in order to optimize EAF operations.

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