ELECTROMETALLURGICAL RELATIONSHIPS IN ELECTRIC SMELTING FURNACES

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ABSTRACT

Electric furnaces used for smelting and those used for scrap melting exhibit different performance profiles in terms of electrical characteristics. However, the underlying principles are the same for either case. The rationalization of these variables is a major concern for furnace operators and designers. This paper presents the results of a two year study of high speed real time data from a number of electric furnaces around the world, covering a very wide range of design philosophy and product manufacture, to provide a better mathematical insight into rationalizing the furnace operation.

1. INTRODUCTION

Two distinguishing types of electric furnaces are utilized in the steelmaking and ferroalloy practices: one is labeled "electric arc furnace" (EAF) and is tiltable. The other is referred to as a "submerged-arc furnace" (SAF) and, while not tiltable, can be rotatable. Their electrical characteristics differ, at the first level, in that the EAF operates on a per-charge basis and the SAF operation is continuous. These differences require appropriate modes of electrical control for their particular metallurgical and thermal requirements. The present investigation attempts to provide a common basic approach to the control aspects– using computer-derived data – particularly, data based on neural network analysis.

1.1 Electric furnace model

Electric furnaces have been built with from one[1] up to six electrodes – in arrays that are linear, triangular, or rectangular. The individual secondary phase windings of the connected power transformers are connected to two electrodes. In the case of a three-electrode furnace, this implies that a delta load pattern is established within the furnace burden. Under normal conditions the current passes from the tip of the electrode to the charge through a small cross section. Once entering the charge, the current flows between electrodes as shown in Figure 1. In so doing it creates sufficient energy to meet the endothermic energy demand of the process. The concentration of the power is greatest at the electrode tips, especially when highly siliceous burdens are encountered. This power density produces elevated temperatures that can lead to the formation of arcs. Nearly isothermal conditions prevail at the tips of the electrodes as the charge shifts continually downward.

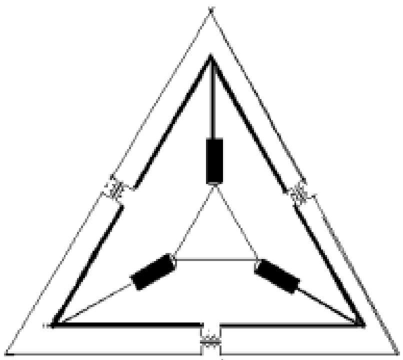

Figure 1. Schematic circuit diagram.

[1] A single-electrode furnace can be treated like one-half of a two-electrode furnace.

The step movement of the charge reveals itself in corresponding changes in the mode of conductance as the arcs are extinguished (or almost) when new charge enters the region of the electrode tips. Electrically, this produces a sequence of arc and Joule (non-arc) modes that alter the ratio of reactive volt-amperes (*VA*r) to power (*W*). Implicit in these variables are, respectively, reactance, *X*, and conductance, *S (1/R),* – important variables for determining conditions within a furnace.

1.2 Diagnostic Values

Inductance (*L*) and Reactance (*X*) — Except when affected by a ferromagnetic environment, the value of *L* (like *S*) is dependent on the geometrical shape of the current path —length and cross section. At a given tap setting, in the absence of arcing, and with two electrode tips located on a plane, the circuit will exhibit a certain value of inductance, L_o. Just prior to the formation of an arc, *L* exhibits a small but abrupt increase in value owing to the constriction of current at each point of arc ignition. Following arc-ignition, *L* increases with arc length, to a certain limiting level – the beginning of a condition described as current chopping. Within the range of continuous current conduction, *L* is directly proportional to the length of the arc, $h_{arc.}$

EAFs generally exhibit higher magnitudes of *L* than SAFs – by a factor of about 4. This difference implies that EAFs operate with longer arcs (especially during the "bore-down" period) than SAFs that are characterized by short, "sputtering" arcs. Since $X = 2\pi f^*L$ (or, ωL). ΔX can also define the length of any circuit segment including that of the arc as long as there are no ferromagnetic materials in the furnace charge. The following chart, in effect, illustrates the relation between reactance and arc length.

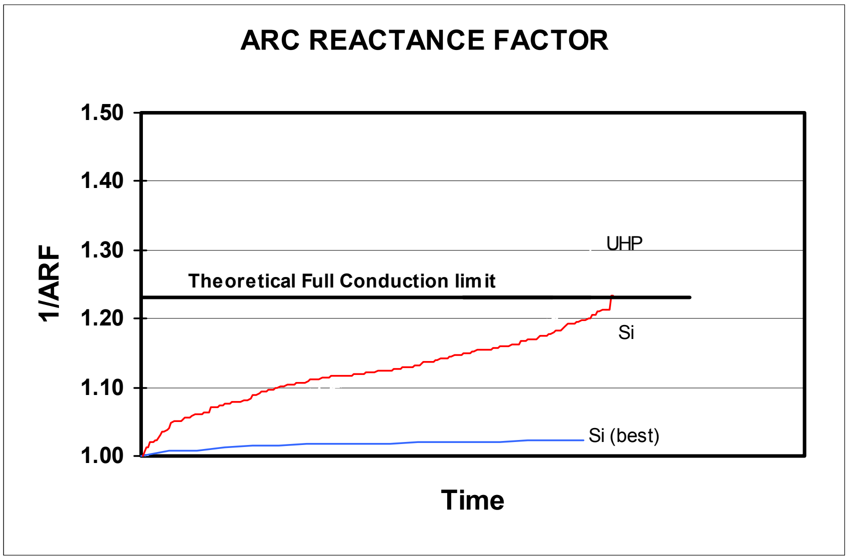

Figure 2. SAF and EAF Reactance.

Note that the SAF data shows a smaller spread than that of the EAF within the linear range. This can be attributed to the shorter arcs and the continuous nature of the operation that characterize SAFs. Overall, an integration constant, $\pi^2/8$, (=1.23) sets the limit for the range in which there is no current chopping. This unique value results from calculations involving arcing with different values of the $X_o{*}S$ parameter, including the limiting theoretical condition for S equal to infinity.

The data that was used to prepare the chart is the basis also for a useful parameter that indicates the degree of arcing: – the "arc reactance factor" (*ARF*). When used in monitoring furnace behaviour the *ARF* serves as an accurate indicator of the relative contributions of arcing and Joule heating:

$$ARF = \frac{X_o}{X} \tag{1a}$$

$$\%Arc = \frac{100(1 - ARF)}{(1 - \frac{8}{\pi^2})} \qquad (1b)$$

The *ARF* is also employed in the construction of furnace power profiles such as the circle diagram (*CD*) that will be discussed later on.

Arc Length (h_{arc}) – The arc is cord-like in shape apparently having a nearly fixed diameter, assumed to be in the range of 10 to 25 mm. Except within a ferromagnetic environment, *Xarc* is proportional to h_{arc} . When the arc becomes too long it reaches a height above which the current becomes discontinuous. However, the corresponding limiting values of h_{arc} for EAFs are higher than those of the SAFs. Therefore, EAF's with delta phase reactance levels of about 12 mOhm can be operated with arc lengths ranging from zero to about 1.2 m.without becoming discontinuous. The corresponding limit for h_{arc} in a SAF, with an *X* level of 3 mOhm, would be 30 cm.

The generally accepted arc voltage-gradient for both EAFS and SAFs is nearly constant at about 1 V/mm as the arc current connects from the electrode to the bath commutating the two phase currents that make up the arc. The validity of this figure becomes clearer when account is taken of the partition between arc- and Joule-power.

Conductance (*S*) — In accordance with the chosen model, the circuit *S* includes, in addition to its principal component charge value, the transformer(s), secondary conductors, electrodes, and the charge contributing about 2% of the total.. The magnitude of S, at some moment immediately following a shift in the burden, depends upon the active area of contact for the transfer of current between an electrode (diameter, d) and the burden. The value of *S* is related directly to the conductivity index of the material in the region of the electrode tips0,[2] i.e., the material contacting the electrode at a temperature determined by the operative metallurgical conditions. Dr. Downing applied the delta configuration to his studies of submerged arc modelling. He was able to replicate furnace data that did not involve arcing. We have been able to extend the delta model to include arcing. Arcing results when the movement of material away from the tip creates a gap. A sequence of this sort lasts a few seconds in an EAF but, in a SAF the duration could be several minutes. The associated change in the magnitude of *X* and *S* cause corresponding changes in the phase angle, as will be shown in the following section.

Phase angle (Φ)The phase angle, Φ, represents the time lapse between voltage-zero and current-zero. It can be expressed as Φ . It can be calculated by applying either of the following equations:

$$\Phi = \tan^{-1}(X * S) \qquad (2a)$$

$$\Phi = \tan^{-1}(\frac{VAr}{W}) \qquad (2b)$$

The critical (arc-ignition) value of *Φ* is the minimum value for sustaining a continuous arc current. This angle is always less than 32.7^o, corresponding to a theoretical condition that implies a resistance-free circuit. With resistance in the circuit the critical angle decreases as the product, X_o*S, decreases. And finally, the changing values of *X* and *S* during operation produce corresponding swings in phase angles.

2. ANALYSIS

Current waveforms — Fourier and oscillographic analysis form the basis of most of the studies related to current and voltage waveforms when arcing is encountered during furnace operations[2]. When arcing is encountered in the secondary phase current, the oscillograms reveal a significant change in shape from that of a normal sine wave.

[2] Excluding magnetic charge components, the value of S depends upon the temperature of the mineral (slag) portion of the charge. In the case of foamy slags however, S decreases as the density decreases.

The current waveform as shown in Figure 3 comprises two components: a sine wave of the same frequency as the power supply and a series of straight lines arranged in a saw-tooth pattern. The straight line represents a completely theoretical circuit condition in which there is no resistance in the circuit – only reactance. With resistance in the circuit the component segments take on an exponential shape.

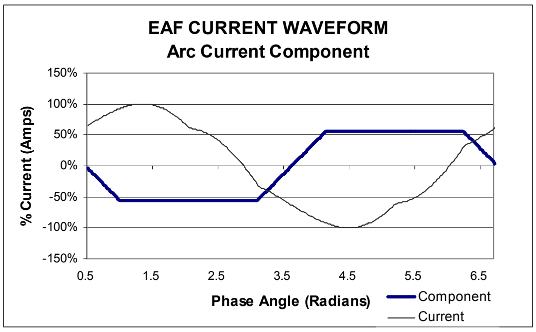

Figure 3. Waveform of a single-phase arc current.

The electrode (arc) current trace shows two discontinuities in one alternation, owing to the vector addition and commutation of the two-phase currents (displaced by 120 electrical degrees) that produce the arc current. The shape of the waveform of the component current is trapezoidal, similar to that of a gear tooth. The straightness of the lines signifies the absence of resistance in the circuit. With increased resistance in the circuit the segments take on an increasingly noticeable exponential form. The total current waveform shows what appears to be a delay at the beginning of each half-cycle. Although the initial instantaneous slope is zero, the change is gradual, as can be inferred from the chart.

2.1 The Circle Diagram

The circle diagram provides a comprehensive view of the most important electrical data related to the operation of both EAFs and SAFs. In the Joule mode the power (*W)* is calculated using three variables *V, X_0,* and Φ :

$$W = \left(\frac{V^2}{2X_0}\right)\sin(2\Phi) \tag{3}$$

. Note that $W_{\max} = \dfrac{V^2}{(2X)}$

The formulation can be modified to include a dimensionless parameter (ARF) that shows the influence of increased arc length on the power level at any given moment. Its inclusion into the above formula incorporates the arc mode into the formulas:

$$\%MaxPower = 100ARF * \sin(2\Phi) \tag{4}$$

Equation (2a) can be modified further into another form to present the relationships between *S* and X_0 and S_0 and X_0 :

$$S = ARF\left(\frac{\tan(\Phi)}{X_0}\right) \tag{5a}$$

$$S_0 = \frac{\tan(\Phi)}{X_0} \tag{5b}$$

As a practical matter, it should be noted that these relationships incorporate collateral events within the furnace. As power is increased the temperature rises in the vicinity of the electrode tips, accompanied by increased charge conductivity and conductance. As a general rule the conductivity of the mineral portion of the charge is more strongly affected by temperature than composition.

An example, based on Downing's research concerning current conduction in furnace slags, presents an interesting temperature pattern in a silicon furnace. (And, by extension, to all types of SAFs and EAFs)

Because of the endothermic nature of the metallurgical process the *S* curve will reveal a preferred range of values for each case. This range remains constant even as the power is increased by applying higher voltage. The corresponding CD curve will indicate the same preferred range of phase angles. Although, as the applied secondary voltage is raised, the entire data field will shift downwards to reflect the change in partition of arc- and Joule-power resulting in an overall increase in arc content.

The equations developed in the preceding conform to the plotted data patterns and clearly define the partition between arc and Joule power. The conductance provides an excellent check of the temperature condition at the tips of the electrodes as the phase angle increases. During operation the data concentrates in a common section of the CD and S charts revealing a sameness despite different charge compositions. Regardless of power level, the nature of the process remains the same owing to the endothermic nature of the process.

The CD charts from SAFs are simpler than those from EAFs because their fixed thermodynamic endothermic demand establishes a uniform temperature field. This enables the CD data to be applied statistically with reference to a mathematically derived window whose height is defined by the partition between Joule and arc energy.

As for the EAFs, the plots can be chosen to correspond to the different stages of the process: establishing the arcs, bore-down (producing a molten pool to serve as working base), creating a foamy slag, melting heavy scrap, and finishing the heat. The essential structures of the two furnace cases are shown below.

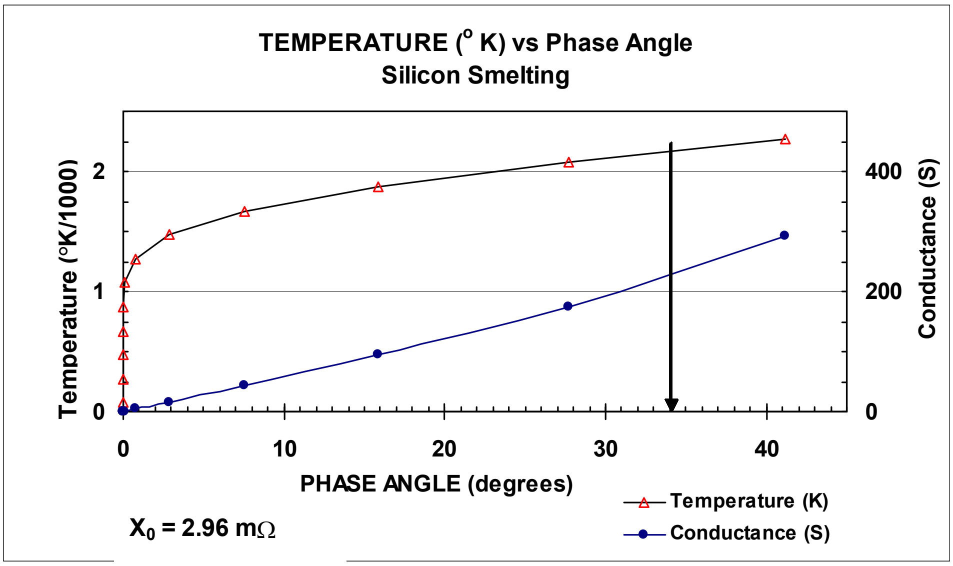

Figure 4. Temperature versus phase angle in SAF.

Figure 4 shows reaction temperature and conductance plotted against phase angle. The conductance curve corresponds to the reactance value of 2.96 mΩ as calculated using equation 5b. The correspondence between temperature and conductance is obtained by equation 6. Note the initial rapid rise in temperature followed by a slower rise. The reaction temperature for the production of silicon is generally accepted to be 2153 °K. The arrow indicates the optimum phase angle for reaching this level.

$$S = 57286e^{-(\frac{12000}{K})} \tag{6}$$

3. SUBMERGED ARC PRACTICE

The smelting of silicon (Si) and its iron-based alloys is a typical example of SAF practice. It involves the smelting of cristobolite at high temperature (about 2153 ^{0}K). Good process performance requires short arcs in order to minimize the production of silicon monoxide (SiO) that represents an energy loss if it is not captured before leaving the surface of the charge. The "sputtering" arc" – operating at the transition point at which Joule conduction yelds to arc formation – is the mode of choice. The chart shown in figure 5 relates to the production of silicon metal in a 20 MVA furnace with a base reactance of 2.97 mΩ. The figure shows a small portion of a circle diagram plot with a plot of conductance superimposed. A full circle diagram was not shown because only a small range of phase angle data is necessary to show the normal operating range of the furnace. The arrow on the chart points to the mean value of the phase angle data.

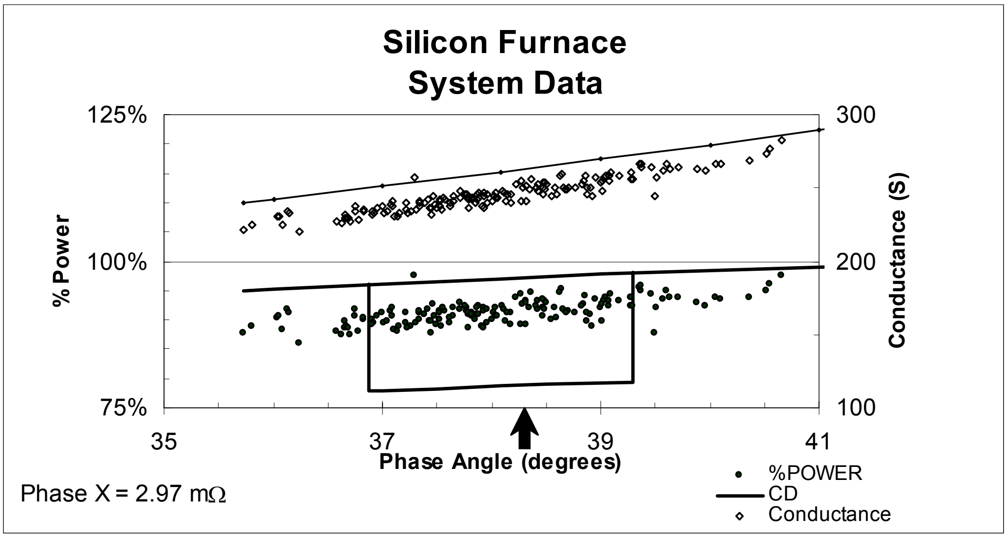

Figure 5. Circle diagram for SAF.

While the chart data was obtained from a specific furnace installation, its format is repeated in all SAFs and EAFs: at all power levels, with different sizes of electrodes, different ranges of conductance, and reactance — all are treatable with the same spreadsheet inputs and the same chart template. Only the levels of conductance change to reflect specific charge compositions and downward movement of the charge.. The SAFs, operate with the tips of the electrodes located nearly on a plane. In fact, the general trend (slow in developing, albeit) is to maintain the tips at a particular level and to adjust the distribution of power by changing individual phase tap settings of the transformers. The electrodes are lowered frequently but only enough to offset electrode consumption. If the electrodes are of the self-baking type the slipping can be carried out in a regular sequence of under 5-cm per hour, thus promoting frequent contact between the electrodes and the descending burden. Iron-free self-baking electrodes are being increasingly employed in the production of silicon metal. Slipping is carried out with shorter increments than in the case of pre-baked carbon electrodes, especially when the latter must accommodate the passage of a joint. In addition, in those installations with the capability of adjusting the phase voltages independently, it is preferable to maintain the columns in fixed positions and make the necessary adjustments by varying the voltages and selective slipping of the electrodes. Rectangular furnaces are fixed, and their electrodes are supported by chains or cables resulting in constant movement of the electrodes. This procedure, it would appear, should eliminate the need for rotating the body of the furnace.

The power increases as the phase angle increases, but above 45^{o} it decreases requiring a change in control tactics. However, the value of S, continues to increase in a region of generally decreasing efficiency.

4. TILTING EAF PRACTICE

In most cases, steelmaking heats are based on smelting a sequence of charges contained in bottom-discharging buckets. One electrode tip is brought in contact with the charge and then another – power usually picks up at this stage – and finally the third electrode makes contact as the three phase currents flow between the electrodes.

The data presented in figure 6 are from an ultra-high powered furnace (530 kVA/MT) high voltage (1200 V secondary) equipped with supplemental series reactance producing carbon steel. The data produce two well-developed patterns of *S* and CD. Up to 45^0 the general trend of the S data shows an increasing temperature at the tips of the electrodes. As the arcs become shorter, more frequent contact is made between the electrodes and the charge burden. Finally, as in the case of the SAFs, the power declines when the phase angle exceeds 45^o. The arrow points to the mean value of the phase angle data, and the number 45 represents the average value of the conductance when arcing is not involved. The operational data selected for the chart was taken during a period where the full supplemental reactor was being used, resulting in a 19.1mΩ per delta phase reactance. Because of the recent trend towards operating EAFs at very long arcs, the operators used this reactor setting during the bore-in process. In this case, it resulted in a lower than required level of power input, and a 12 mΩ per delta phase reactance would have served better.

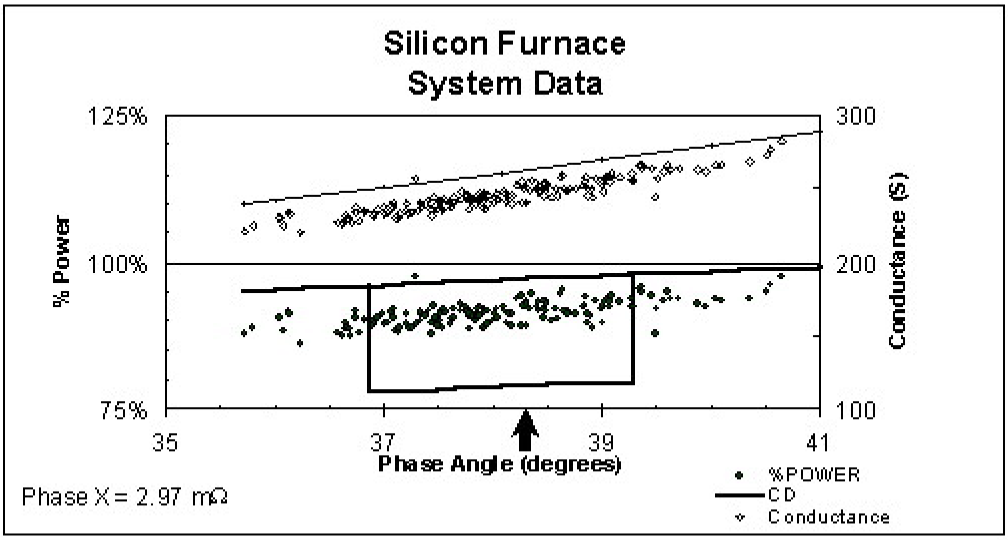

Figure 5. Circle diagram for EAF.

An interesting phenomenon also enters the process when heavy scrap or bundles make up a portion of the charge in an Ultra-High Powered (UHP) Furnace[3]. As the electrodes probe deeper into the charge the magnetic field produced by the electrode induces circulating currents in the heavier charge components. This coupling is reflected in a reduction of the secondary reactance and explains the data points above *S* and CD curves.

5. CONCLUSION

For over 100 years the electric arc furnace was mainly a smelting tool. Comparatively recently it has developed into a multi-functional, quick-melting, machine with pre-treatment of the charge, oxy-fuel burners, and procedures for producing foamy slag. In addition, the disadvantages associated with earlier tilting mechanisms have been greatly reduced owing the adoption of the Eccentric Bottom Tapping (EBT) feature that makes it possible to limit the tilt angle to below 15^o. This last feature has also resulted in better control over pouring and improved shrouding of the metal being tapped. Each of these features has their counterparts in SAF practice. The ability to translate process behaviour into suitable electrical signals is still undergoing improvement. The goal is to control the process as opposed to just managing it.

Modern computer programs, especially those that involve neural network analysis[4] can process real time data with great accuracy. It has become possible to examine furnace operation in real time at locations remote from an electric furnace installation that has matching data acquisition capability. The purpose of this paper has been to demonstrate some of the precise relationships that have been established between such data and the associated physical events that occur out of view within the furnace burdens.

The employment of a common model for batch melting (EAF) and continuous smelting (SAF), emphasizes the importance of recognizing the delta load character of both types of furnaces. The importance of *S* and X (in terms of delta values) was demonstrated with regard to the basic nature of smelting technology. Each process has its characteristic *S* profile and in conjunction with *X* and ARF, a more appropriate control strategy for each type of furnace and its unique operating demands can be established.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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