cmp TECHCOMMENTARY

Vol. 3, No. 2, 1987 Published by the Center for Metals Production — An EPRI Sponsored R&D Applications Center

Understanding Electric Arc Furnace Operations For Steel Production

Introduction

The use of electric arc furnaces (EAF) for steelmaking has grown dramatically in the last decade in the United States. In 1975 electric furnaces accounted for 20% of the steel produced in the U.S.; by 1985 this figure had grown to 34%. Electric furnaces range in capacity from a few tons to as many as 400, and a steelmaking shop can have a single furnace or up to three or four. In brief, these furnaces melt steel by applying an AC current to a steel scrap charge by means of graphite electrodes. It requires about 500 kWh of electricity to produce a ton of steel; consequently, these furnaces use a tremendous quantity of electricity. Transformer loads may reach 120 MVA.

The melting process involves the use of large quantities of energy in a short time (1-2 hr) and in some instances the process has caused disturbances in power grids. These disturbances have usually been characterized as "flicker" — brief irregularities in voltage a fraction of the 60 Hz cycle in length, and "harmonics" — irregularities that tend to occur in a pattern repetitive to the 60 Hz cycle.

The features of electric arc furnaces were described in a CMP TechCommentary on Electric Arc Furnaces (Vol. 1, No. 3, 1985). The purpose of the present TechCommentary is to give utilities and steel mills a better understanding of electric furnaces from an electrical viewpoint.

Energy Needs

Furnaces are often classified by power requirement levels. A scale indicating power classification ranging from ultra-high-power (UHP), with over 700 kVA per ton, down to low-power, with less than 200 kVA per ton, is shown in Figure 1 along with some representative furnaces.

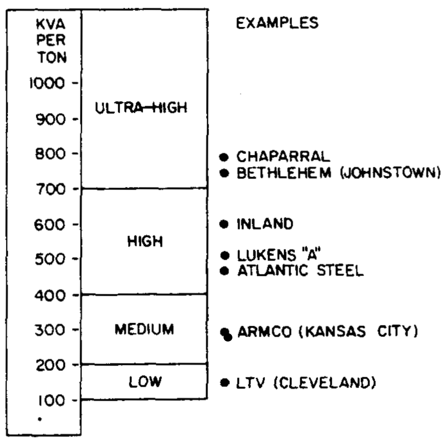


Figure 1
EAF Power Classifications

It is important to consider the energy balance for a typical modern EAF. The energy diagram shown in Figure 2 indicates that 70% of the total energy is electrical, the remainder being chemical energy arising from the oxidation of elements such as carbon, iron, and silicon and the burning of natural gas with oxy-fuel burners. About 53% of the total energy leaves the furnace in the liquid steel, while the remainder is lost to slag, waste gas, or cooling.

Typical tap-to-tap time has decreased from over 2 hours in 1960 to 70-80 minutes today. Primarily responsible are UHP furnaces, oxy-fuel burners, water-cooled side panels (which allow for higher power after the steel is molten), foamy slag practices (which also permit higher power), and ladle metallurgy (which removes the refining function from the furnace and shifts it to a ladle into which the molten metal is poured).

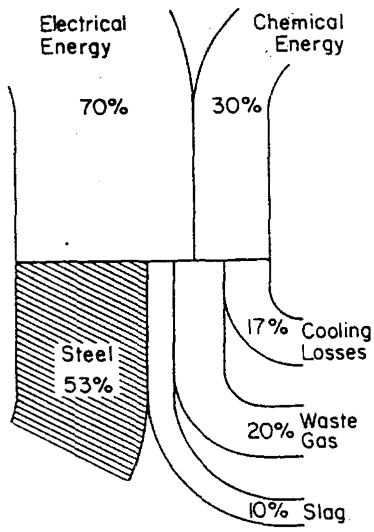
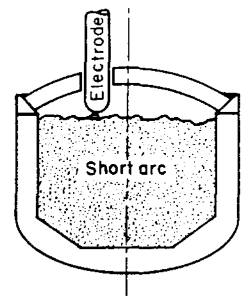
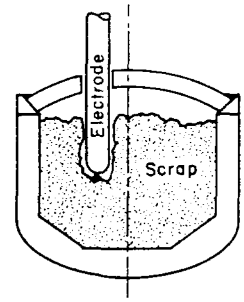
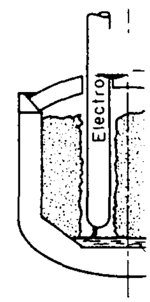
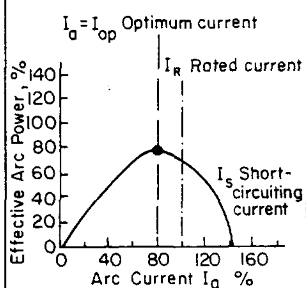
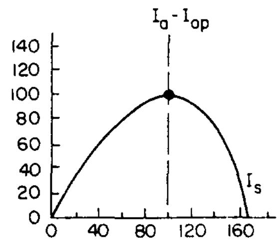
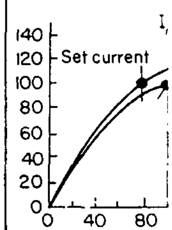
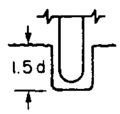


Figure 2
Energy Patterns in an Electric Furnace

Typical Steelmaking Cycle

A typical heat cycle appears in Figure 3. To achieve meltdown as quickly as possible, electrodes are initially lowered to a point above the material, the current is initiated, and the electrodes bore through the scrap to form a pool of liquid metal. The scrap itself protects the furnace lining from the high-intensity arc. Subsequently, the arc is lengthened by increasing the voltage to maximum power. Most modern furnaces are equipped with water-cooled panels in the upper half of the sidewall, rather than refractories, which allows for longer arcs and higher energy input into the furnace. In the final stage, when there is a nearly complete metal pool, the arc is shortened to reduce radiation heat losses and to avoid refractory damage and hot spots.

After melt down, oxygen usually is injected to oxidize the carbon in the steel or the charged carbon. This process is an important source of energy; the carbon monoxide that evolves helps minimize the absorption of nitrogen and flushes hydrogen out of the metal. It also foams the slag, which helps minimize heat loss.

Period / Item	Arc ignition period (start of power supply)	Boring period	Molten metal period
Conditions of furnace			
Operating objectives	1. To protect the furnace roof from arc 2. To stabilize the arc 3. To rapidly submerge the electrode tip into scrap	1. To promote rapid melting by supplying high power and increasing the boring speed 2. To increase the boring diameter	To protect the furr from arc spot
Characteristic curve of arc power			
Criteria for operation of furnace	 To be judged by the position where the electrode tip is submerged for about 1.5d	1. The rate of lowering the electrode 2. The lowered position of the electrode	To be judg ... consumption (kW the boring period

Courtesy of the Iron and Steel Society, Inc. — **Electric Furnace Steelmaking — 1985**

Figure 3 Steel Melting Cycle

Detailed Electrical Operation

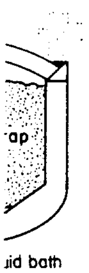
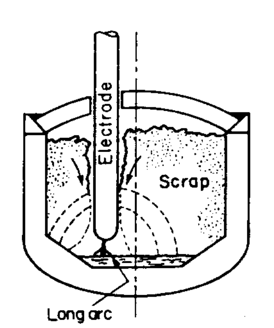
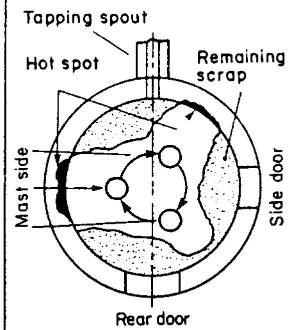
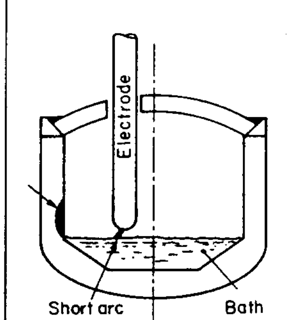
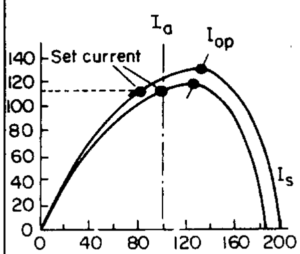
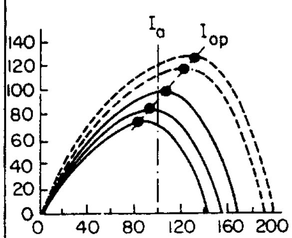
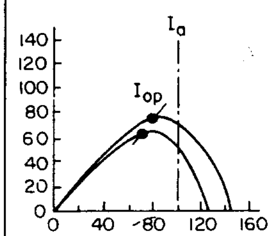
After an electric furnace is charged with scrap and the roof is in place, the operator lowers the electrodes, each of which has its own regulator and mechanical drive. The electrodes are connected to the furnace transformer's secondary delta winding, which may be rated from about 600 to 850 volts.

No current flows when the first electrode contacts scrap, but a line-to-line path through the scrap and an arc are established when the second electrode completes the circuit. The regulators for each of these two electrodes then signal the drives to raise the electrodes until the selected current-voltage ratio for the arc is achieved. Initiation of the third arc depends on the scrap's location, which is unpredictable, hence the duration of the unbalance is short but random. While the scrap is still unmelted, the arc may easily be extinguished by a minor overshoot in an electrode regulator or by physical movement of the scrap. As the scrap melts, it can often shift and fall away from an electrode — extinguishing the arc, or against the electrode — possibly breaking it.

Because of the physical movement and settling of the scrap, wide excursions can take place on a random basis in the secondary circuit. The abrupt initiation and interruption of current flow provides a source of harmonic currents and causes considerable disturbance to high-impedance circuits. (About 75% of the total impedance is in the secondary circuit.) Voltage and current waves deviate considerably from symmetrical sinusoidal patterns, but they do not attain full rectangular shape, according to findings in the CMP report, "Arc Furnace Power Delivery Scoping Study."[1] Disturbances are worst during early meltdown, and they occur at varying frequencies.

Many attempts have been made to establish the human eye's reaction to the flicker of a lamp. That these endeavors have not exactly confirmed one another is shown in Figure 4 (from "Arc Furnace Power Delivery"), where perception is measured while disturbance voltage and frequency are varied. Eye response to disturbances in the 5-10 Hz range did seem to be greatest in all the studies.

Generation of harmonics may result in further flicker problems, and equipment on the power system may also be damaged. If static capacitors are to be used to improve the power factor, an analysis to ensure that resonance does not exist at any of the harmonic frequencies should be made. Harmon-

·mation	Main melting period	Meltdown period	Meltdown-heating period
			
· bottom	Since the arc is surrounded with solid materials, the the thermal conductivity of arc power is a maximum. Therefore, rapid and uniform melting should be planned by supplying the maximum power that the facilities permit	1. To reduce the local damages near hot spots on lining 2. To rapidly melt the remaining scrap	1. To reduce the heat radiation onto the lining as well as minimize hot spot damage 2. To rapidly increase the temperature of molten steel to the appropriate value for refining
			
powe ifter	1. Variation of arc impedance 2. The rate of the F'ce temperature (IPB) 3. Power consumption (kWh)	1. Power consumption (kWh) 2. Melting conditions of scrap	Power consumption (kWh)

Borderlines of flicker per perceptibility for incandescent light bulbs under laboratory conditions (1-Commonwealth Edison, 120V, 25 + 40 + 60W; 2-Japan, 100V, 60W; 3-Schwabe, 120V, 60W; 4-Carjell, 220V, 60W; 5-Wasowski, 220V, 40W; 6-Kendall, 230V, 60W; 7-UIE, 230V, 60W; sinusoidal wave; 8-UIE, 230V, 60W, square wave).

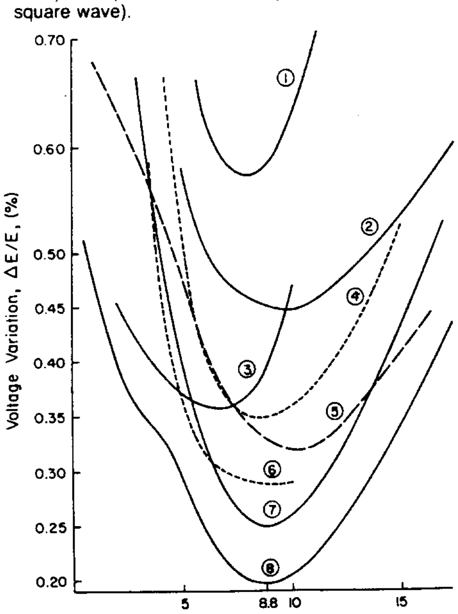


Figure 4
Borderline of Flicker Perceptibility

ics contribute to wave distortion and to the increase in effective inductive reactance. This increase is often in the 10 to 15% range and has been reported as high as 25%. Current into the furnace is therefore less than what would be expected from calculations based on sinusoidal wave shapes, and losses in frequency-sensitive equipment such as transformers are higher than the sinusoidal wave shape would produce.

Importance of Scrap

Scrap is available in a wide variety of sizes, densities, and chemical compositions, and a mixture is usually used. If only the lightest, least dense material is charged, several buckets of scrap must be placed in the furnace to make a full heat. This is generally uneconomical due to oxidation losses and the need to open the furnace for several separate charges, which results in loss of both time and heat. Nor is the use of large heavy scrap alone optimum. A large piece might protrude and interfere with roof closure or require placement by magnet, a process which takes time.

The furnace operator therefore tries to blend several types of available scrap to suit his needs. It is beneficial to arrange the heavier pieces near the bottom of the charge. After about 20 minutes of operation, depending on available power and other practices, the electrodes will have opened some voids, and cave-ins can occur. If large pieces of scrap are on top of the pile, they can possibly slide into and break an electrode. It is generally believed that light, uniform scrap produces a smoother meltdown than does large heavy scrap. However, this is not always the case. If heavy scrap is charged, full power can be applied. If all the scrap is light, on full power the electrodes may bore through, damaging the furnace bottom before a sufficient pool of liquid metal has formed. Generally, the initial period of melting causes the most electrical disturbances. As the scrap temperature begins to rise, a liquid pool forms, and disturbances begin to diminish. This is generally about 10 minutes or so after power-on and can vary depending on power levels and shop practices.

Melt Down

Heating steel scrap to approximately 3000° F requires large quantities of energy rapidly applied. Therefore, full power is called for during meltdown. The arc during meltdown can be long because the electrode and arc are boring a hole down through the scrap, and the roof and sidewalls are not exposed to arc radiation. If the arc is extinguished, the regulator will lower the electrode to re-establish it. This can take several seconds if the scrap has moved out from under the electrode.

Main Melting Period

After about 20 minutes, most electric furnaces will have begun converting scrap to liquid metal. Hence, wide swings in disturbances will diminish considerably. When sufficient molten metal exists (in some high-powered furnaces only 8-10 minutes is required), the arc is shortened by an adjustment to the electrode regulators. The current will rise since overall resistance is reduced, and the power factor and arc power will decline. Arc length is changed so that the shorter arc will deliver a higher portion of its heat to the metal below the electrode than will the longer arc, which radiates more heat to furnace sidewalls. Many studies have been conducted which confirm the advantages of the long arc for meltdown of heavy scrap and the short arc for operation after sufficient liquid metal has been formed. The short arc is much more stable than the long arc, and operation during the refining period follows sinusoidal concepts much more closely.

Arc Movement

Photos have been taken during the refining period to show the electric arc's action. High-speed photography is needed to capture the 60 arc cycles per second. It has been shown that the arc moves around on the tip of the electrode and, in some cases, considerably off the vertical. This movement is believed to be caused by the electromagnetic forces induced by the high current flow (Figure 5). When the same conditions were observed with hollow electrodes, the arc still moved around considerably, but it appeared to be more nearly vertical and better consolidated than with solid electrodes.

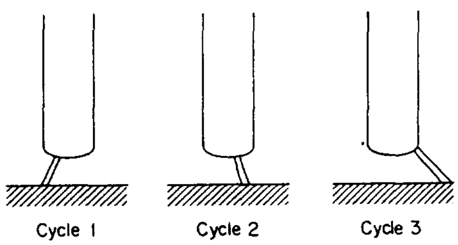


Figure 5
Arc Pattern Flow

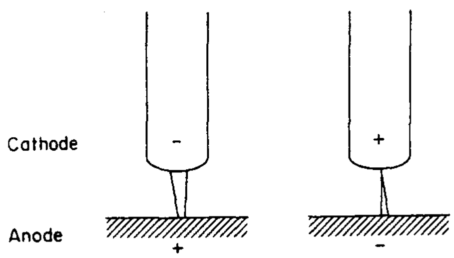


Figure 6
Variation in Arc Shape with Half Cycles

When the carbon electrode acts as the cathode, it is a good emitter of electrons (hence, carbon cathodes in the large mercury arc rectifiers of several years ago); steel, even molten, is not nearly as good. During the half-cycle when the scrap or the bath is the cathode, arc initiation is a little slower and weaker than when the electrode is cathodic (Figure 6). This slight variation between the opposite half-cycles tends to create the even-numbered harmonics — the second and fourth.

Reducing Electrical Disturbances

Many ways exist to reduce the effects of the arc disturbances. These are determined by the utility system to which the furnace or furnaces are to be connected, and they are influenced mainly by the size and stability of the power grid. Some sizable shops require no particular flicker control equipment. It is quite possible that, if a furnace shop is fed from a 220 kV or higher system with a short-circuit capacity of 6500 MVA or more, the utility will experience very little load disturbance, and the steelmaker can have considerable flexibility in configuring his internal plant power system.

Most utilities require power factor correction. Shops with large electric furnaces would more than likely use static capacitors; synchronous condensers of sufficient capacity would be prohibitively expensive for a multifurnace shop. Before such systems are installed, transient analysis is required to determine:

(a) Capacitor bank configuration
(b) Need for harmonic tuning of sections
(c) Switching procedure (This is important to avoid a power factor penalty and does not eliminate flicker.)

If additional regulation is needed, VAR control equipment would probably be required. However, if plans have already been made for power factor capacitors, including tuning reactors, then the thyristors and main reactor are the only further additions required.

Other Means of Reducing Flicker

Preheating the scrap charge helps reduce electrical disturbances in melting and removes some contaminants (such as oils) and low-boiling-point nonferrous metals. Preheat could come from waste heat or supplemental gas or oil burners.

The recent trend toward using the electric furnace as a main melting unit has led to the practice of leaving some slag and molten metal in the electric furnace. CMP-AISI studies at Sidbec-Dosco indicated that this practice reduces arc furnace flicker.[2]

Argon and Lime Injection

Tests have been run with hollow electrodes, both dry and with argon, and argon and lime injection. Work by W.E. Schwabe in the 1950's demonstrated the stabilizing effect of hollow electrodes in furnaces.[3] He described the development of the trumpet profile in the tip which decreased load swings during meltdown.

Trials with hollow electrodes and argon injection during the 1970's showed a marked smoothing of oscilloscope traces of arc voltage and current[4]. The favorable effect of argon resulted from the arc-supporting effect of the media due to the greater number of atoms present for ionization. Injection of powdered lime into the arc zone cut arc resistance in half and eliminated all high-frequency components of the arc voltage.[1]

Based on these favorable results, trials on a commercial-sized electric furnace were undertaken by the Center for Metals Production, with joint financing by 20 steel companies and the Electric Power Research Institute.[2] A 20% reduction in flicker was found when argon and lime were injected down the electrodes during these tests. However, savings in power and electrodes were minimal, offering little incentive for adopting this practice for steelmelting.

DC Furnaces

Operation of an electric furnace with one direct-current electrode rather than the three electrodes of conventional alternating-current designs has proven to reduce electrical system disturbances. Improvements in load variation, a 60% reduction in flicker, and elimination of phase unbalance has been reported with DC furnaces.[5] Major problems with DC operation are the relatively short life of the bottom electrode and contact between the scrap and the bottom electrode during initial meltdown. Except for the bottom electrode, most of the equipment for a DC furnace is conventional, and large DC loads are now routinely handled in steel mills. A 60 MW furnace load would be comparable to rectifiers supplying a wide 7-stand hot strip mill for rolling steel.

Rectifiers for these main 3000-5000 hp drive motors are of the 12-pulse type. These rolling mill systems handle large impact loads which are close to step functions and probably could handle initial disturbances in DC melting furnaces.

EAF Furnace Loads Are Not Unreasonable

It is true that the arc furnace incurs short circuits. However, relative magnitude should be kept in mind: If current at maximum circuit power is considered to be 100 percent, or 1.0 per unit, then a short circuit will result in only 1.414 times this full load current — not too serious a problem. When the primary breaker is closed on a transformer, the inrush current can be 10 times rated load — far more than the 1.4 times due to a secondary short in the electric arc furnace. A hot strip rolling mill can go from no load to 60 MW faster than a 60 MW furnace, and this can occur every 2 minutes. While the rolling mill load is a balanced-phase load (a major advantage over arc furnaces), the mill load cycles much more frequently.

Utility Engineering Progress

Most of the larger electric arc furnaces installed over the past 20 years have been fed from high-voltage, stiff utility power grids. Problems of previous years — transformers failing because of resonance on a certain tap combination or utility capacitor banks failing far from an offending furnace — have not been repeated. Users and utilities have done their homework prior to installation, and potential problems have been identified and corrected. The user can decide what to do inside his plant regarding the potential flicker problem. For example, he may want to install harmonic filters, which would also help avoid power factor penalties. It is also helpful that makers of electronic apparatus - computers, TV, X ray, etc.—have improved their power supplies in recent years, making these systems less vulnerable to power fluctuations.

Most important, utilities have become vitally interested in power quality. To further this goal, the Electric Power Research Institute has formed a Power Electronics Applications Center to investigate further the question of utility power quality.

Bibliography

1. "Arc Furnace Power Delivery Scoping Study," Center for Metals Production, Report No. 84-1, 1984.
2. "Arc Stability in Electric Furnace Steelmaking," Center for Metals Production, Report No. 86-9, 1986.
3. W. E. Schwabe. "Experimental Results with Hollow Electrodes," Iron and Steel Engineer, June 1957, pp. 84-92.
4. W. J. Maddever. "Gas Injection Process During Electric Furnace Steelmaking and Continuous Casting," Ph.D. thesis, University of Toronto, 1978.
5. "DC Arc Furnaces for Steel Production," Center for Metals Production, Report No. 86-8, 1986.
6. "Techno-Economic Assessment of Electric Steelmaking Through the Year 2000" EPRI, 1987 (to be published).

CMP Publications of Interest

84-1 Arc Furnace Power Delivery (1984)

A detailed analysis of the technical problems relating to large electric furnaces and utility power grids.

85-1 Ladle Refining Furnaces for the Steel Industry (1985)

A review of supplemental steel heating and refining units often used in conjunction with electric arc furnaces.

85-2 Electric Arc Furnace Dust Disposal (1985)

An analysis of dusts generated by electric furnaces and a review of methods for treatment and disposal.

Vol. 1, No. 3 Electric Arc Furnace Steelmaking (TechCommentary - 1985)

A description of the structure and function of electric arc furnaces.

86-7 Electrode Tip Analysis (1986)

An examination of electrode wear by various photographic means.

86-8 DC Arc Furnaces for Steel Production (1986)

A comparison of the electrical energy consumption of a conventional 30 ton AC furnace with a 30 ton DC furnace.

86-9 Arc Stability in Electric Furnace Steelmaking (1986)

Field testing the effect on furnace performance of hollow electrodes, lime and argon injection, and changes in other operating parameters.

The Electric Power Research Institute (EPRI) conducts a technical research and development program for the U.S. electric utility industry. EPRI promotes the development of new and improved technologies to help the utility industry meet present and future electric energy needs in environmentally and economically acceptable ways. EPRI conducts research on all aspects of electric power production and use, including fuels, generation, delivery, energy management and conservation, environmental effects, and energy analysis.

The Center for Metals Production (CMP) is an R&D application center sponsored by the Electric Power Research Institute (EPRI) and administered through Mellon Institute of Carnegie Mellon University. CMP's goal is to develop and transfer technical information that improves the productivity and energy efficiency of U.S. primary metals producing companies (SIC 33). Target areas are reduction/smelting; refining/remelting; and surface conditioning/protection.

EPRI
Robert Jeffress, Project Manager

CMP
Joseph E. Goodwill, Director
Richard M. Hurd, Chairman Steelmaking Processes
James M. Hensler, Manager of Technical Projects
John Kollar, Manager of Communications
William C. Flora, Consultant
David J. Westhead Company, Inc./ Advertising

cmp
Center for Metals Production
Mellon Institute
4400 Fifth Avenue
Pittsburgh, PA 15213-2683
412-268-3243

CMP-0787-002