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The High Current D.C. Arc in Extractive Metallurgy

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Abstract

The use of high current electric arcs in furnaces for the extraction of metals is briefly reviewed. The recent history of d.c. open-arc furnace applications in extractive metallurgy is given together with a general description of the construction and operation of this type of electric furnace. The advantages and obstacles to utilizing higher voltage operation in these furnaces leads to a requirement that the fundamental behaviour of d.c. high current arcs in hot furnace environments should be better understood. The theoretical and experimental studies carried out in this field, including the contribution of Szekely and co-authors, is reviewed. It is concluded that further research and development work in developing dynamic models of arc behaviour and associated measurements of these model parameters should be undertaken. This information can then be applied to the design of the power supply equipment for d.c. arc furnaces to improve arc stability and allow higher voltage operation. The influence of feed materials and foamy slags on arc column behaviour would also be valuable in further improving the performance of d.c. arc furnaces.

1. Introduction

The electric arc exists in many widely differing conditions e.g. lightning, circuit breakers, welding machines, and furnaces. They may extend across kilometres or millimetres, from a few amperes to hundreds of kiloamperes and from single volts to hundreds of kilovolts. The research carried out on electric arcs tends to be directed at specific applications because of the widely differing nature of the arc and this paper will concentrate on the use of direct current (d.c.) electric arcs in furnaces for the extraction of metals from ores, concentrates or slags.

The first electric arc furnaces were in fact d.c. furnaces(1, 2) which reflected the form in which electric power was distributed at the time. The rapid shift to alternating current (a.c.) furnaces similarly reflected the development of the electric power supply industry.

Electric furnaces have been predominantly a.c. for almost a century because of the prohibitive cost of rectifying a.c. current. The development of solid state thyristors for rolling mills and electrolytic plants(1) has increasingly made the use of d.c. electric furnaces an economically viable alternative over the past twenty years. The implementation of d.c. electric arc furnaces began in the mid-1980's for the melting of steel scrap and by 1995 more than forty d.c. arc furnaces for this purpose had been installed(3) . These units range in capacity from 40 to 200 tons of liquid steel and up to 80MW in electric power. This application is therefore well established industrially and has been well described in the literature(1,3,4).

The use of electric furnaces for smelting rather than scrap melting involves the extraction of metals from ores, concentrates or slags and often requires the addition of a carbonaceous reductant to reduce metal oxides from the slag phase. The range of various furnace types which have evolved to meet the widely varying process requirements has been well described by Matyas et al(5). These authors have classified the a.c. smelting furnaces as follows:

a) immersed electrode - pure resistive heating, no arc present
b) open-arc - most energy dissipated in an open-arc above the slag
c) submerged-arc - micro-arcing to a coke bed underneath a porous bed of high electrical conductivity charge materials
d) shielded-arc - long arcs shielded by low electrical conductivity, free-flowing charge materials

These furnaces have benefited from a long history of incremental improvements and have attained high levels of electrical energy utilisation in large units, e.g. less than 10% steady state heat losses to the furnace hearth, walls and roof at power levels of 40 to 80MW. A primary measure of furnace intensity is the power flux i.e. electrical power input per unit of furnace hearth area, which lies in the range of 70 to 470 $\mathrm{kWm^{-2}}$ for typical a.c. smelting furnaces(5). This is however much lower than scrap melting furnaces where typical power fluxes of 1,5 to 2,0 $\mathrm{MWm^{-2}}$ are employed.

Immersed electrode furnaces generally have a low intensity ($< 130\ \mathrm{kWm^{-2}}$) largely due to their strong dependence on slag resistivity to generate power at any given electrode spacing. Slag resistivity tends to decrease with rising temperatures so there is a natural limitation on the power density that can be generated by pure slag resistance heating.

Higher power fluxes ($\sim 500\ \mathrm{kWm^{-2}}$) have been attained in the shielded-arc or submerged-arc furnace type where the bulk of the energy is generated in the electric arc. The use of an electric arc as means of introducing large quantities of energy into a furnace at high temperatures therefore provides an opportunity to increase the productivity and efficiency of electric smelting furnaces. However, this intense heat within the arc must be effectively transferred to the charge materials rather than being lost to the furnace walls or roof.

Some significant process restrictions are however imposed by the use of shielded or submerged arc furnaces and the open arc furnace has increasingly been used to overcome these obstacles(2). Processes which evolve large quantities of gas from the reduction reactions (usually carbon monoxide) require that incoming feed materials form a burden above the arc that is sufficiently porous to allow the gases to escape without generating dangerously high pressures in the reaction zone. A build-up of pressure can result in very damaging explosions. This need to maintain a porous burden requires that the fraction of finely sized materials (usually defined as <6mm) be restricted. The shielded-arc mode of operation requires that the incoming feed materials should have a high electrical resistivity and be free-flowing(5). This is because of the high voltages employed which essentially restricts the fraction of carbonaceous materials in the feed. It is best suited for processes where little further reduction of metal oxides is required. Typically processes where more than 50% of the feed materials are smaller than 6mm in size and contain more than 10% carbonaceous materials by mass cannot effectively utilize the shielded or submerged-arc electric furnace configuration.

The open-arc furnace is therefore required for the high intensity smelting of these types of materials e.g. chromite or ilmenite concentrates using anthracite as a reductant. The open-arc furnace could be either of a d.c. or an a.c. type and in fact both these types are used industrially for ilmenite smelting(2). The d.c. open-arc furnace offers the following advantages over an a.c. open arc:

a) simplicity in that fewer graphite electrodes are utilized (usually one instead of three),
b) lower electrode consumption,
c) no electro-magnetic interaction between arcs and
d) greater arc stability.

The electro-magnetic interactions between a.c. open arcs leads to mutual repulsion of the arc columns and an asymmetrical distribution of heat in the furnace(1). This requires that the feed materials be distributed over the slag surface to match the distribution of heat and prevent local over-heating of furnace side wall refractories. The d.c. arc furnace if operated with a single electrode provides a central largely symmetrical input of heat which simplifies the feed system arrangement. The greater stability of a d.c. arc allows higher arc voltage and lower current operation to be adopted with a further reduction of electrode consumption.

2. The D.C. Arc Furnace Smelting Applications

The first d.c. arc smelting furnace was a 16 MVA unit installed at Palmiet Ferrochrome(6) in South Africa in December, 1983. The furnace was uprated to 40 MVA in 1988 and its subsequent successful performance has been well described by Ford and Oosthuizen(6). The furnace produces ferrochromium from chromite fines (100% < 6mm), coal and fluxes. An operating load of 26 MW at an availability of 90% had been achieved by 1994. A second d.c. arc ferrochromium smelter commenced operation in 1997 at Samancor's Middelburg Ferrochrome plant.

The smelting of bag-house dusts arising from stainless steel plant operations in a d.c. arc furnace has also been successfully demonstrated(7). Two plants are in operation in England and Italy producing chromium and nickel bearing ferrous alloy from the bag-house dust and a carbonaceous reductant.

The smelting of ilmenite concentrates in a d.c. arc furnace commenced operation in 1995 at Namakwa Sands in Saldanha, South Africa(2). The installation of a second d.c. arc furnace at the same site has recently been announced(8).

These applications all treat feed materials typically less than 3mm in particle size and use carbonaceous reductants to reduce various metal oxides to form a ferrous alloy, a slag and carbon monoxide gas.

2.1 General Description

The arrangement of a d.c. arc smelting furnace as used at Mintek for process development and demonstration is shown schematically in Figure 1. This general arrangement is fairly typical of industrial furnace installations(1).

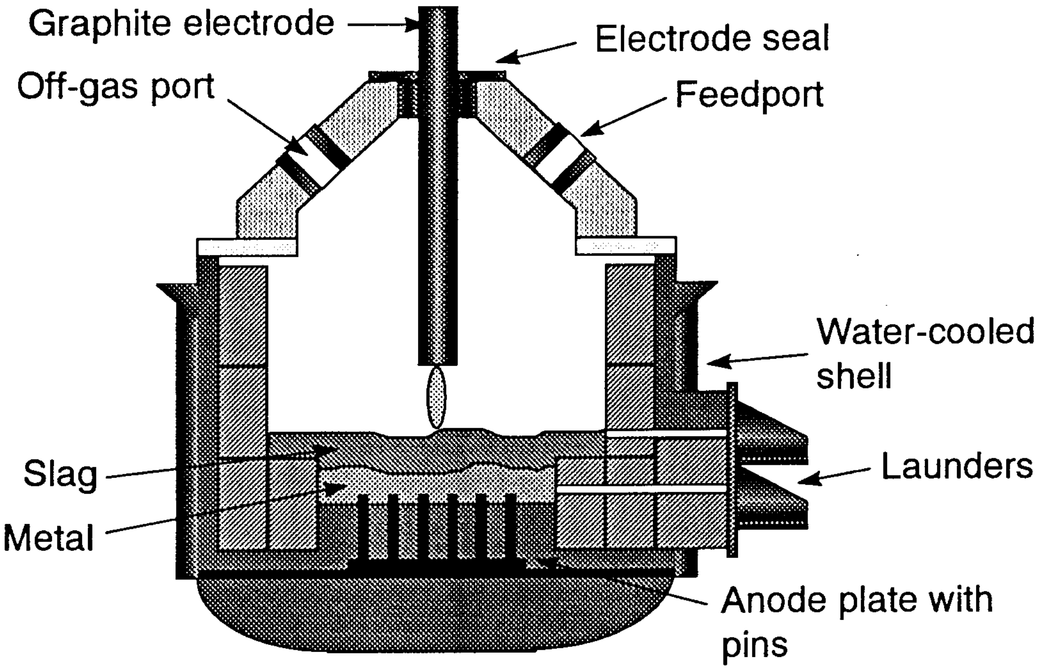

Figure 1: Schematic arrangement of Mintek's d.c. arc furnace

All of the current smelting applications use a single graphite electrode connected as the cathode to a rectifier with an anode connection installed in the hearth of the furnace. The graphite electrode is installed centrally in a circular furnace shell that is lined with refractory materials(9). The power supply consists of a step-down transformer, a thyristor rectifier and a reactor(1, 10), (connected in series between the rectifier and the furnace). A number of different anode connections within the hearth of the d.c. furnace have been developed(11) which utilise electrically conductive refractory bricks, steel clad bricks or various configurations of steel rods, billets or plates embedded in rammable refractories.

There is a substantial difference in anode duty requirements between the melting of steel scrap and smelting furnaces. Scrap melting furnaces operate with a relatively small residual mass of metal remaining in the furnace after tapping, which is achieved by tilting the furnace. Smelting furnaces are able to retain a substantial depth of metal in the furnace below the metal tap hole level and are not tilted. This large mass of electrically and thermally conductive metal serves to protect the anode connection and consequently while scrap melting furnaces routinely replace the anode connection every one to three months(3, 11), d.c. arc smelting furnaces anodes have operated for more than five years without requiring replacement. They are essentially designed to operate indefinitely. Anode connections are an area of major concern(3) and considerable design effort in scrap melting furnaces(11) but not in d.c. arc smelting furnaces.

The graphite electrode operating above the bath may be hollow and used to direct the feed materials into the arc attachment region at the surface of the liquid slag. This mode of operation is used for ferrochromium smelting(6) while Figure 1 shows a feed port (of which there may be several) located in the roof as an alternative arrangement.

Operation of these smelting furnaces is usually one of continuous feeding of raw materials at a rate matched to power input with intermittent tapping of the accumulated slag and metal (every 2 to 4 hours). Power input is effected at Mintek by careful and rapid control of the rectifier at effectively fixed electrode positions. This is complemented by much slower adjustments to the electrode position to maintain a constant average furnace voltage. Power level and furnace voltage are the set-points adjusted by the operators as required.

Electrical insulation is provided on the Mintek furnace by means of a suitably sized refractory element between the electrode and the water-cooled roof. The anode is connected directly to the furnace shell and maintained at earth potential. This practise differs from some major industrial furnaces where the anode connection is also insulated from the furnace shell(1, 6).

2.2 Operational Limits

It is clearly advantageous to utilise fewer but larger furnaces to reduce the operating costs but also to increase the smelting intensity to minimize the capital cost of such large units. The d.c. arc smelting furnace is limited by the maximum power that can be supplied by a single graphite electrode (currently in the range of 40 to 50 MW). This is a function of the maximum current and voltage (typically 100 kA and 450 V). The current limit is imposed by the diameter and quality of the graphite electrode, until recently the maximum available size was 650mm at 100 kA. This has now increased to 730mm with a current capacity of up to 140 kA(3). Increasing furnace power by means of increased current carries little technical risk but has major cost implications since electrode consumption increases with current(3) and power supply capital cost is strongly linked to maximum current. There is therefore a strong motivation to increase the operating voltage. This is effectively the sum of the voltage drop across the slag layer and the voltage drop across the arc for the d.c. open arc furnace, if the voltage drops across the metal bath, the anode connection and the bus bars are neglected. The voltage drop across the slag is largely dependant on the current, the slag resistivity and depth.

Many of the smelting applications utilize slags of fairly low resistivities at the furnace operating temperature and the major proportion of the total operating voltage drop occurs across the open-arc struck between the slag surface and the electrode tip. The arc voltage is generally increased by raising the electrode and extending the arc length, however arc stability decreases with increasing length and eventually the arc extinguishes.

One of the major problem areas identified(6) in scaling up the 16 MVA ferrochromium furnace to 40 MVA was stray arcing onto water-cooled components of the furnace roof. Ford and Oosthuizen(6) noted that this problem had not been observed on the 16 MVA furnace which operated within a lower voltage regime. It would seem that stray arcing may be a limiting factor on the use of extended arc lengths to achieve higher operating voltages. The stray arcing phenomenon was also identified during the early stages of d.c. arc furnace development at Mintek⁽⁹⁾ in 1983.

It may be concluded that high voltage d.c. arc furnace operation will require some combination of a) increasing the arc length without generating instabilities and b) increasing the characteristic arc voltage gradient. These alternatives both require a more fundamental knowledge of the behaviour of the d.c. arc itself.

3. D.C. Arc Behaviour in Smelting Furnaces

An equation describing the static characteristics of open air arcs was proposed.

$$V = 30 + 12L + 120L/I$$

where

V = arc voltage, volts
L = arc length, cm
I = arc current, amps

Three examples of this characteristic are shown in Figure 2 for arc lengths of 1, 10 and 100 cm.

The general behaviour of an electric arc was well described by Browne(12) in 1955.

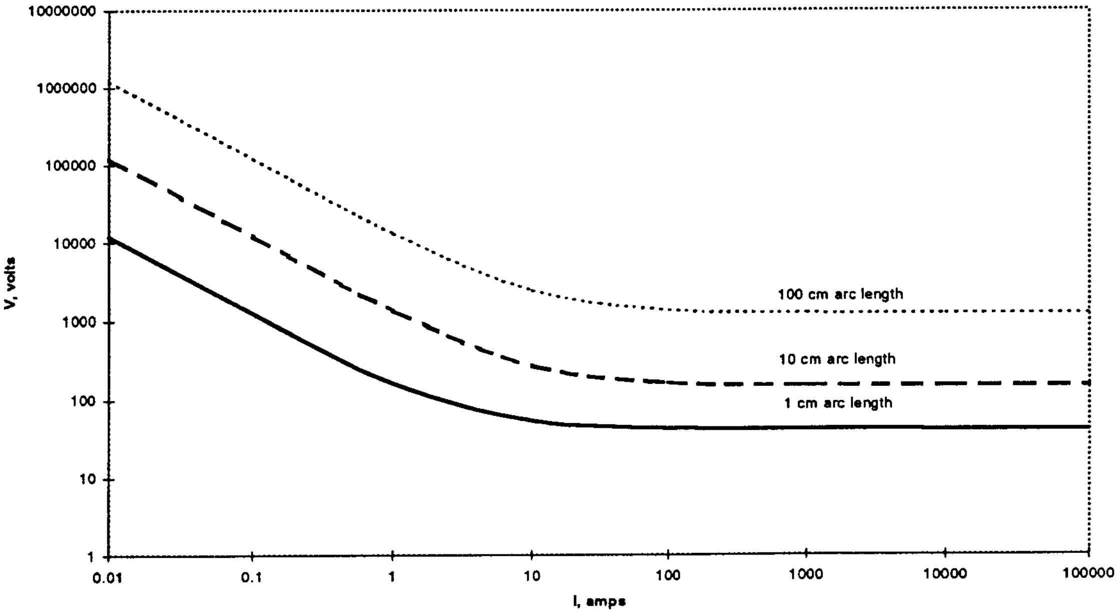

Figure 2: Static characteristics of open air arcs after Browne(12)

It can be seen that above arc currents of 100 amps the characteristic simplifies to $V = 30 + 12L$ which is the familiar form encountered in d.c. arc furnaces. The constant voltage term can be assigned to electrode effects at the surface of the anode and cathode. The 12V/cm constant relating the arc voltage to arc length is in good agreement with the equivalent value of 11V/cm measured by Bowman et al(13) in a laboratory study aimed at scrap melting furnace behaviour. The low current behaviour is however of interest in arcs approaching extinction and may be very significant in understanding arc stability.

3.1 Dynamic Arc Behaviour

Browne(12) also describes two mathematical models of the arc which can be applied to electrical circuit equations to estimate the dynamic behaviour of the arc as a circuit element. These models are based upon the assumption that for a unit length of arc column the conductance of the arc column is related to the stored energy content of the arc. These models (by Mayr and Cassie respectively) express the dynamic behaviour of the arc at low and high currents.

$$\frac{dR}{dt} - \frac{R}{\Theta} = - \frac{E^2}{\Theta N_o} \qquad \text{Mayr's model}^{(12)}$$

and

$$R \frac{d}{dt}\left(\frac{1}{R}\right) = \frac{1}{\Theta}\left[\frac{E^2}{E_o^2} - 1\right] \qquad \text{Cassie's model}^{(12)}$$

where: R = arc column resistance per unit length ($\Omega.cm^{-1}$)
E = arc column voltage gradient ($V.cm^{-1}$)
t = time (secs)
E_o = characteristic column voltage gradient ($V.cm^{-1}$)
N_o = constant power loss per unit length ($W.cm^{-1}$)
Θ = arc time constant (secs)

The constants E_o and N_o can be equated to the constants 12V/cm and 120W/cm in the static arc characteristics of Equation (1) for open air arcs. Browne(12) has estimated that the value of the time constant (Θ) is approximately 300μsec by analysing the behaviour of a 15kA, 60Hz arc in air for circuit breaker applications. It is interesting to note that a theoretical model of lightning discharges(14) concluded that a time constant of 100μsec characterised the time required for a temperature perturbation at the core of the arc to diffuse to its periphery.

This tends to support Browne's view that the time constant is a characteristic arc constant not primarily dependant on the current magnitude.

Browne(12) also showed that a fixed impressed voltage would always result in arc instability either towards an open circuit or a short circuit. This was extended to show that there is a critical value of applied voltage gradient above which the arc resistance approaches zero instead of infinity which could be considered a break-down value.

3.2 Fundamental High Current Arc Behaviour

The pioneering work of Bowman et al(13) in 1969 produced data on the behaviour of the electric arc in steelmaking conditions from 2kA to 10kA in the laboratory and up to 50kA in a commercial steel scrap melting furnace. It was shown that the current density at the cathode spot on the graphite electrode was $2.4kAcm^{-2}$ at a d.c. current of 2kA total. The arc diameter of an a.c. arc with a peak current of 7.8kA was approximately 3cm at a distance of 10cm from the graphite electrode tip. A theoretical model of the arc column by Ushio, Szekely and Chang(15) showed good agreement with the experimental data of Bowman et al(13). This showed that a 2kA d.c. arc of 7cm in length would have axial centre-line velocities of approximately 1000ms^{-1} decaying radially to 100ms^{-1} about 0.8cm from the arc centre-line. The temperature in the arc column varied from 15000K to 10000K along the arc centre-line

Stenkvist and Bowman(16) presented empirical data from d.c. arc scrap melting furnaces, operated between 10 and 20kA, on the relationship between arc voltage (100-270V) and length (6-30cm) which indicated a characteristic gradient of 4 to 6 Vcm^{-1} which is significantly lower than the 11 to 12V/cm range determined for open air arcs by Browne(12) and Bowman(13). A substantial difference may be expected given the high temperature surroundings (~1600°C) and the change in gas composition (CO/CO_2 vs N_2/O_2) encountered in a scrap melting furnace. The rate of heat loss to the surroundings should be expected to be substantially lower in a 'hot' environment. This same range of voltage gradients (4 to 6V/cm) has been found during smelting tests at Mintek to prevail for a number of different smelting processes at similar furnace temperatures and in atmospheres high in carbon monoxide (~90%).

It is known that the introduction of metallic vapour species into the arc can decrease the voltage gradient(17). It has also been stated(16) that feeding charge materials down a hollow electrode (for ore fines reduction) cools and deionizes the arc thereby increasing the voltage gradient.

Bowman(18) has also shown that the effect of submerging an arc in slag as commonly practised in scrap melting furnaces significantly increases the voltage gradient (up to 9,0V/cm in a.c. furnaces) due to the cooling effect of the slag 'walls' on the submerged arc volume. The voltage gradient in submerged d.c. arc operation was observed to be even larger (13V/cm) which was attributed by Bowman(18) to a smaller arc volume and more effective cooling by the slag 'walls'.

The relationship between voltage gradient and arc diameter was also investigated by Bowman(18) for arcs submerged in liquid slag. The calculations indicated arc diameters of 10cm and 15cm for a 60kA a.c. arc at voltage gradients of 10 and 6 V/cm respectively. This calculation depends upon estimates of the net radiation loss from large diameter (>2cm) arcs for which the assumption that they are optically 'thin' does not hold and for which self-absorption effects are substantial. It would appear that further data on gas mixtures more typical of arc furnace conditions, to better estimate the net radiative loss as well as the electrical conductivity of d.c. arcs, would be valuable.

4. Conclusions

The d.c. single electrode arc furnace is an attractive option for smelting applications because of its lower graphite electrode consumption, simplicity of operation and lower maintenance costs. These furnaces are limited in maximum power however, by the availability of larger sizes of graphite electrodes. The development of a self-baking Söderburg electrode for open-arc d.c. operation could remove this limitation.

High current operation is however expensive in terms of capital cost and electrode consumption and higher voltages as a means of attaining higher power levels would be economically advantageous. There are however potentially major process obstacles in terms of damage to the furnace structure by stray arcing and higher heat losses to the furnace roof refractories.

There are two principal means of effectively increasing the operating arc voltage: a)increase arc length and improve arc stability by means of improved power supply design as well as improved electrical insulation in furnace construction; and b) increase the arc voltage gradient by increased cooling of the column or decreasing the electrical conductivity of the gas mixture in the arc. Feed selection and position relative to the arc, or submerging the arc in a foamy slag are possible methods of achieving the former while the introduction of elements with high ionization potentials may accomplish the latter.

There is a need for research and development in the following areas to assist in further improving the performance of the d.c. arc furnace in smelting applications:

- The development of dynamic models of the arc, based on fundamental principles
- The measurement of primary arc parameters to validate the dynamic arc models
- The use of these models to optimise the power supply circuit design and control system
- Improved understanding of arc radiation as a function of arc diameter, arc column elemental composition and interaction with solid feed particles to improve the applicability of arc models to actual furnace conditions
- Investigate the feasibility of employing foamy slags in d.c. smelting arc furnaces to submerge the arc column and increase the voltage gradient.

5. Acknowledgement

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