

THE APPLICATION AND SCALE-UP OF A.C. AND D.C. SMELTING FURNACES FOR FERRO-ALLOYS

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INTRODUCTION

The prices of ferro-alloys, as with most commodities, have fallen significantly over the past twenty years. This has forced many plants to close or cut costs dramatically to survive. Technology has played a critical role in this cost reduction. Improved feed material preparation, larger and more efficient submerged arc furnaces, changes in post-taphole practices, and advanced process control have all had major impacts on the industry. There would seem to be advantages of scale by going larger still, but to achieve this, a different approach will be needed, as any further advances with conventional technology would seem to be rather limited.

Submerged-arc furnaces continue to be used for ferro-alloy production. These furnaces typically use three-phase alternating-current power, fed in through three electrodes arranged in a triangular configuration. There would seem to be advantages of scale with these furnace operations, but various limits of capacity are now being encountered with the conventional technology, and these are becoming a hindrance on the construction of larger units. In the case of high-carbon ferromanganese, for example, it would seem to be very difficult, if not almost impossible, to achieve operation at power levels above about 40 to 50 MW¹. With silicon, which also has a relatively low electrical resistance, the limit would seem to be about 25 to 30 MW, while with high-carbon ferrochromium, which has a higher resistance, the present limit would seem to be up to about 70 MW. By comparison, the largest steel-making arc furnaces are currently of the order of 80 to 100 MW, and this figure would seem to be still rising.

In the case of high-carbon ferromanganese, this constraint on furnace size means that it is difficult to get a yearly production per furnace of more than about 140 to 160 thousand metric tonnes per annum. When this is compared to the rate of production of pig iron from a modern blast furnace, which is typically of the order of 2 to 3 million metric tonnes per annum, but in some cases is up to 5 million tonnes per annum, it is evident that the capacities of even the largest submerged-arc furnaces are small in comparison. Questions arise as to why this is the case, and whether ferro-alloy furnaces could or should be made any larger.

In this paper we illustrate how some of the constraints on conventional submerged-arc furnaces can in principle be relaxed through the use of d.c. power. In addition we indicate the potential benefits of d.c. furnace technology to the ferroalloys industry.

It is convenient conceptually to split the characteristic curves of a ferro-alloy process into those of the power supply and those of the furnace. From the practical perspective of the power supply, it is possible to get either an a.c. or a d.c. power supply that can deliver power in almost any region of this characteristic curve graph where the furnace may require it. However, it has been found that as the process is scaled up, so the operating point seems to move into areas of these characteristic curves that inherently incur operational problems from the furnace side. Two particular problems that have been identified are the current-carrying capacity of the electrodes and the interaction effect in the control of the electrodes. In theory, d.c. power should help to alleviate both of these problems, as this paper will attempt to explain in more detail. However, d.c. has some problems of its own, and there may be still more hidden problems that will become evident only once these more obvious constraints have been removed. This paper will discuss some of these possibilities.

THE FURNACE CIRCUIT

Consider a section through a furnace around one electrode, as shown schematically in Fig. 1, with an electrical supply to that one electrode. At this stage, let us ignore the issue of how this supply is brought in, except to say that it can be done either through a connection to the floor of the hearth, or via a return path through other electrodes in the same furnace.

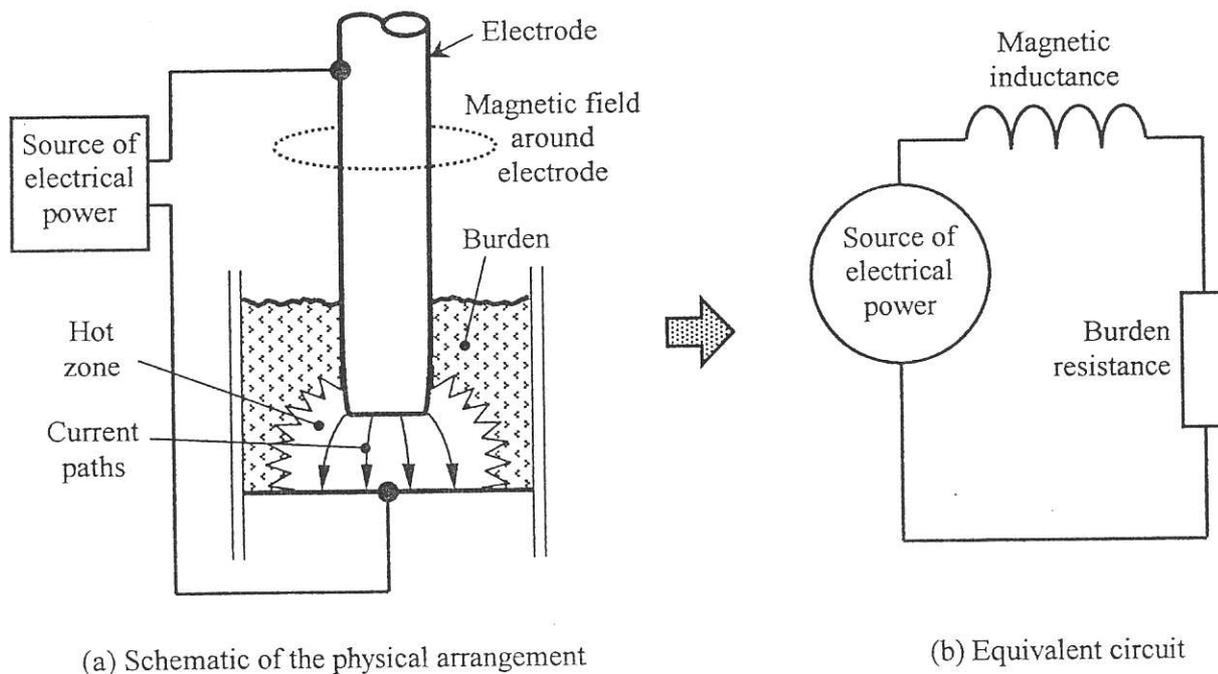


Fig. 1: Conduction through one electrode of the furnace, and its equivalent circuit.

In this furnace circuit, the power supply creates a voltage between the top of the electrode and the hearth. This voltage drives the current to flow through the electrode and then through the burden to the hearth. The majority of the electrical power is dissipated in the hot zone of the burden beneath the electrode, and there is therefore a significant voltage drop between the tip of the electrode and the hearth. The current flowing

around the circuit creates a significant magnetic field around the conductors, and this reveals itself as an electro-magnetic inductance in each phase. Any a.c. current flow through this inductance creates an additional a.c.-voltage drop. However, in the case of d.c. power, the inductance is of little importance as it does not produce a steady-state voltage drop.

Characteristic curves

A graph can be drawn of the power dissipated beneath this electrode against the current flowing through the electrode, as shown in Fig. 2. The process itself will have one characteristic curve while the power supply will have another as indicated. The operating point will be the point at which these curves intersect (provided that they do, and that the point of intersection is a stable operating point).

The gently upwards-curving line in Fig. 2 is fairly typical of the shape of a furnace characteristic curve, as will be discussed in more detail below. The inverted-U-shaped curves in Fig. 2 are typical of an a.c. supply with a magnetic inductance in series with the furnace load, and fed from a fixed voltage source. If the voltage of the supply is changed while the remainder of the circuit is kept fixed, a different curve is obtained. The other two inverted-U shaped lines in Fig. 2 are two examples of this. Hence, by tapping the transformer voltage up or down, it is possible to move the operating point along the furnace curve. Thus, in theory, it is possible to provide power in almost any region of the characteristic graph where it may be required. Furthermore, by tapping the supply voltage up, both the power and the current increase.

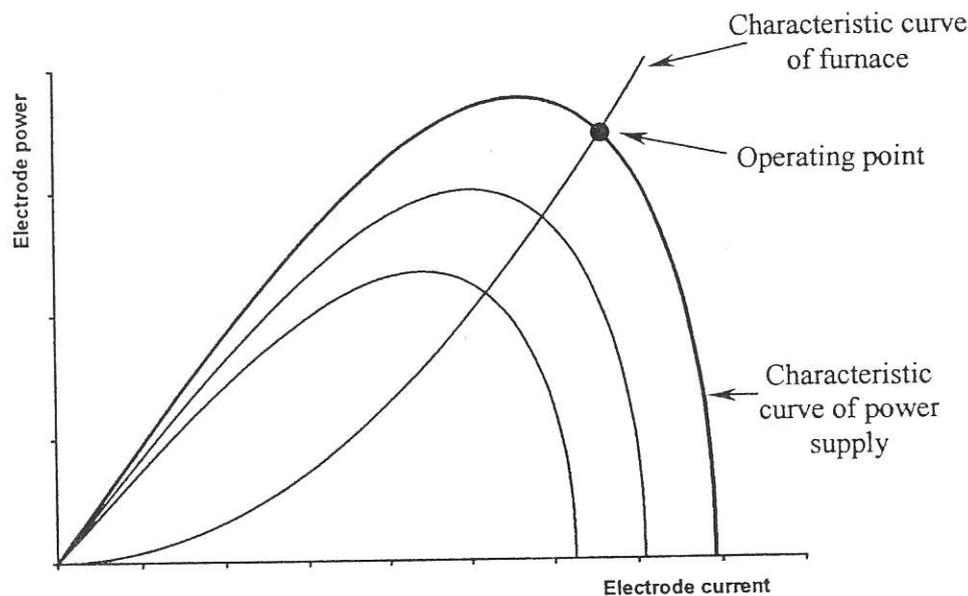


Fig. 2: An example of the characteristic curves for the furnace and the power supply

Trends in furnace sizes

The ferro-alloys industry employs a great number of furnaces, operating on many different products. The operating points of these furnaces show that each distinct process has a characteristic power-versus-current curve. Fig. 3 shows some observed trends for ferrosilicomanganese, 75% ferrosilicon, silicon, and two types of ferrochromium processes. Related trends have been documented previously²⁻⁵.

An extrapolation of the trend lines beyond the ranges shown in Figure 3 indicates the region where any future expansion in the size of furnaces will take place.

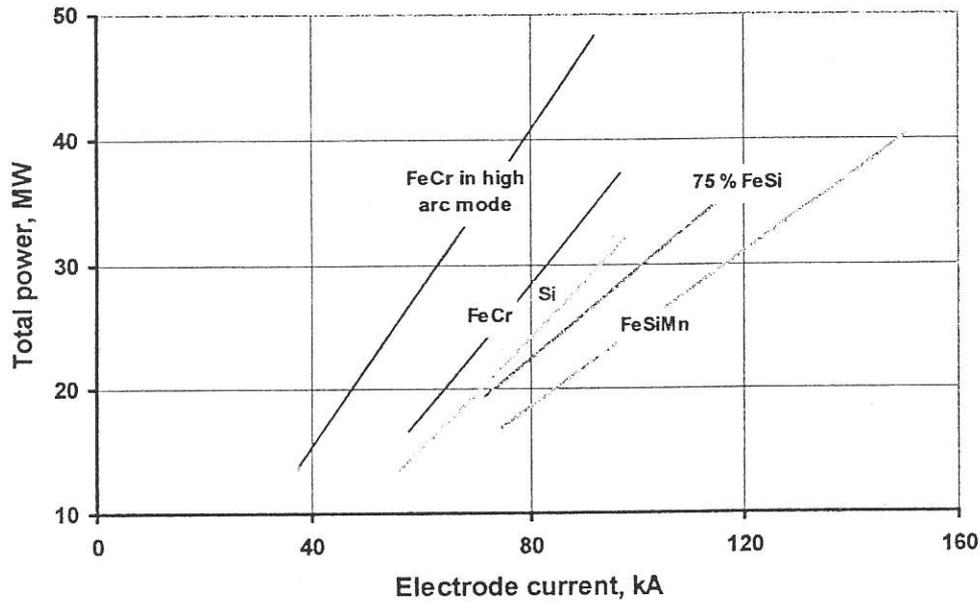


Fig. 3: Trends for five different ferro-alloy processes, on a graph of total power vs. electrode current.

Constraints on the Operation

The concept of a multiplicity of constraints has been described by De Waal et al.⁶ It also applies to the issue of scaling up of a ferro-alloy furnace. In particular, when some factor that is limiting the process is extended, the operation is often unable to make full use of this extension, because the operating point then encounters another different limitation.

The following five factors have been suggested as being the major constraints on the maximum size of present submerged-arc furnaces:

1. The current-carrying capacity of Søderberg electrodes,
2. The resistance of the burden,
3. The reactance of the power supply circuit,
4. The gas permeability of the burden, and
5. The energy generated by the combustion of the furnace off-gases.

Of these, the reactance of the power supply is probably the main constraint. The current-carrying capacity of the electrodes also appears to be a major limitation, but in reality it may be the reactance problem in another form that appears as a limit on the electrode size. The resistance of the burden is in most cases essentially fixed, but there are some variations that can be considered. The gas permeability and the combustion of the off-gases may be further complications, but these can possibly be accommodated.

CHARACTERISTIC CURVES OF THE FURNACE PROCESS

Denote the current through the electrode by i , and the power dissipated in the furnace by this current as P_E (NB: this may not be the same as the total power P_T in the furnace as a whole). If the conduction path of the current through the furnace behaves as a resistor of resistance R_E , then the following equation would relate the power to the current:

$$P_E = i^2 \cdot R_E \quad (1)$$

On the other hand, the power-dissipating element may act more like an arc. Arcs are complex phenomena electrically, but from a simplistic viewpoint, the arc tends to behave somewhat less like a resistor and more

like a constant-voltage device. In this case, if this voltage is V_a , the following equation would relate the power to the current:

$$P_E = i.V_a \quad (2)$$

Based on actual data collected from furnaces, Westly proposed the C_3 factor as another possible formula to describe the characteristic curves of the furnace⁴. This relationship can be re-written for a single electrode as:

$$P_E = i^{1.5} / (3 \times C_3^{1.5}) \quad (3)$$

(It is evident that the functional form of equation (3) is a compromise between equations (1) and (2)).

The above three relationships all indicate that:

- the greater the current, the greater the power, and
- at a given current, the larger the magnitude of the power-dissipating element (i.e. the higher the resistance, or arc voltage or reciprocal of C_3), the more power.

Accordingly, to raise the power dissipation in a furnace, one should look at ways to both increase the current in the electrode, and increase the magnitude of the power-dissipating element (e.g. the resistance) between the electrode and the hearth.

Limits on Current per Electrode

The dominant factor that determines the maximum current is the diameter of the electrode. Other factors, such as the quality of the paste, the design of the casings, the rate of slipping, and the operation of the furnace, also have an influence, but are minor by comparison. Hence to increase the current-carrying capacity, it is basically necessary to increase the electrode diameter.

Despite all attempts to improve the electrode technology over the years, Andreae's original formula for the limiting current in a Söderberg electrode is still used². This can be converted to metric units and re-arranged, to relate the limiting current I_E in kA to the diameter of the electrode D_E in metres, as follows:

$$I_E = 55 \times D_E^{1.5} \quad (4)$$

At present, the largest sized Söderberg electrodes used in submerged-arc furnaces are typically around 1.7 to 1.9 metres in diameter. From equation (4), it can be shown that these correspond to current capacities of about 122 to 144 kA respectively. However, it is questionable whether this formula can still be used to predict the capacities of electrodes that may be larger than about 2.0 metres in diameter, as it has never been tested or verified in this region.

The main consequence of exceeding the current-carrying capacity of a given size of electrode is that the risk of an electrode break increases significantly, although excessive current is not the only factor that can cause an electrode break. If an electrode breaks, not only does it affect the production from the furnace, but also it may upset the metallurgy and so produce off-specification material. It would appear that larger electrodes are more susceptible to breaking. Furthermore, the upset to the operation may also trigger another break, and so lead to a vicious cycle of electrode breaks that is difficult to recover from, but here the interaction effect (as is described in more detail below) probably also plays a role.

We suggest that there are two direct reasons why a larger Söderberg electrode tends to give more trouble than a smaller one, viz.:

1. The strength-to-weight ratio deteriorates as the electrode is scaled up.
2. The skin effect distorts the distribution of the current flowing in the electrode.

Strength-to-weight ratio - The weight of the electrode rises by the cube of a linear dimension (e.g. the diameter), while the strength rises by the square of this dimension. That is, the strength-to-weight ratio falls in proportion to the reciprocal of the dimension as the electrode gets larger. Hence electrodes become relatively weaker as they get bigger. It would appear that there is no simple solution to this problem.

Skin effect - The skin effect refers to the tendency of a.c. current to keep to the outside of a conductor. It does not occur with d.c. current. It is caused by voltages induced within the conductor by the fluctuating magnetic field associated with the current flowing in the same conductor. (This effect should not be confused with the forces on a current-carrying conductor in a magnetic field, as in the so-called 'motor rule'). The skin depth is a measure of the depth to which this current flow penetrates below the surface of the conductor. This skin depth δ is given by:

$$\delta = \sqrt{\frac{\rho}{\pi \cdot f \cdot \mu_0 \cdot \mu_r}} \quad (5)$$

where ρ is the specific resistivity of the conductor, f is the frequency of the a.c. current in Hertz, μ_0 is the magnetic permeability of free space, and μ_r is the relative permeability of the conductor. By substituting typical values for these parameters, it can be shown that for Söderberg carbon and pre-baked carbon, the skin thickness is about 0.3 to 0.4 metres, while for graphite it is about 0.15 metres.

For any electrode where the radius is larger than the skin thickness, the skin effect will be significant. Fig. 4 shows some calculated current densities across Söderberg electrodes for a range of diameters. This figure assumes that all the relevant physical properties are uniform across the electrode, and is based on the typical properties in the carbon stump of the electrode. Although the curves obviously do not strictly apply to the baking zone of the electrode, they do indicate that there may be problems with the baking towards the centres of the larger electrodes because of the deficit of current in these centre regions. It is evident from Fig. 4 how the skin effect plays an increasing role as the diameters get larger. Also, because the current is then concentrated in the skin layer at the surface, the heating from the $i^2.R$ dissipation of power is greater, and so the electrode gets slightly hotter relative to the corresponding d.c. case.

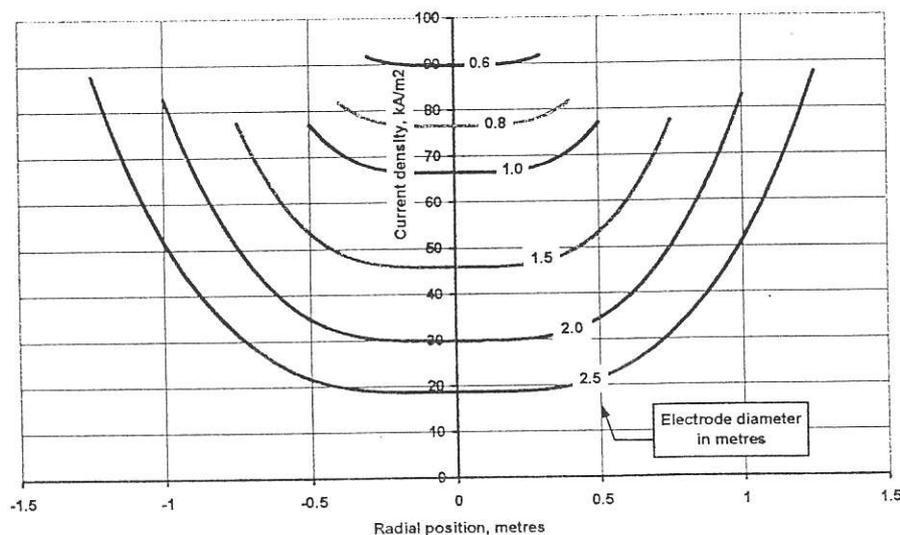


Fig. 4. Current densities across a Söderberg electrode for various electrode sizes, at 50 Hz. (The total electrode current for each diameter is specified from equation (4).)

With d.c. power the skin effect does not occur (as can be shown by substituting $f=0$ in equation (5)), which indicates that large electrodes may tend to behave better in a d.c. furnace. Conversely, smaller diameter electrodes would behave similarly using a.c. and d.c. as their current densities would be uniform in both cases.

Graphite electrodes can carry almost double the current of Søderberg electrodes of the same diameter, and hence are a definite alternative. A comparison of power input using Søderberg and graphite electrodes for ferrochrome and ferromanganese production in a submerged-arc furnaces shows that with graphite electrodes, roughly double the power can be achieved at the same current. At present, the largest graphite electrodes are 0.8 metres in diameter (capable of carrying 140kA), but if the demand was there, larger diameters could perhaps be manufactured. It may be possible to set off the high cost of graphite electrodes against the considerable productivity increases that would ensue. Probably the greatest challenge for the operator of a ferro-alloy furnace with Søderberg electrodes is to balance the baking-slipping rates of the electrodes, as required to maintain electrode lengths. Pre-baked and graphite electrodes do not have this limitation, because they can be slipped as much or as little as required.

In conventional a.c. submerged-arc furnaces at present, the electrode diameters are only one of many constraints on furnace size. Other constraining factors, in particular the interaction effect (as explained below), are probably more critical. However, if d.c. power were used, then it is very possible that the electrodes would be called upon to carry even higher currents, and this would require that they be made significantly larger. We suggest that, for Søderberg electrodes, diameters up to about 2.5 metres might be considered with existing technology, and possibly even larger diameters in future as experience grows around the operation of such electrodes. As an indication, equation (4) indicates that a 2.5 metre electrode should be able to carry about 217 kA with a.c. and this current would probably be even higher with d.c.

Limits on the electrical 'resistance' of the burden

By 'resistance' here, we are referring in a generic sense to any one of several possible measures of the extent to which the contents of the furnace resist the flow of current when a voltage is applied. This 'resistance' will depend on the interaction between the metallurgical processes that occur in the hearth, and the mode of electrical conduction and dissipation of this power in this same region. The mechanisms will vary not only from one type of ferro-alloy process to another, but also from one type of raw material to another.

It is beyond the scope of this paper to report a detailed study of the conduction mechanisms for each of these types of process. In summary, however, raising the electrode will raise the 'resistance' in all cases, but this will also affect the metallurgy. Hence for most existing types of ferro-alloy process, with given raw materials and a given type of process, there will be an optimum band for the value of the resistance beneath the electrode. It will usually be desirable to operate towards the upper end of this band simply to get as much power in as possible, but it is not possible to increase the resistance indefinitely without adversely affecting the metallurgical performance.

In some cases, it may be possible to change the metallurgy to obtain more of an open-arc type of process. By this means, significantly higher voltages can be achieved. For example, a ferro-alloy like ferrochromium, which is normally made via a wet process in a submerged-arc furnace, can also be made in a d.c. arc furnace. In this case, the voltage on the furnace can be made significantly higher if the process is operated in an open-arc mode, or in a mixed conduction mode as appears possible for high power ferrochromium production.

CHARACTERISTIC CURVES OF THE POWER SUPPLY

The essential parts of the equivalent circuit of a conventional a.c. power supply are summarised in Fig. 1(b). In practice, there is more than one electrode – typically three. The full equivalent circuit will then consist of a star arrangement with a common hearth, and the source of electrical power is then a three-phase supply brought in a symmetrical phasor fashion to the three electrodes. However, except for the asymmetrical interaction effect as discussed further below, the characteristic behaviour of such multi-electrode furnaces is the same as for the single-phase equivalent circuit shown in Fig. 1.

Magnetic inductance behaves as a reactance circuit element in an a.c. circuit, and this involves a voltage drop when a current flows. Hence as the furnace draws current, so the voltage available to the furnace decreases. At high resistances and low currents, the voltage drop across the reactance is negligible, and so the power dissipated in the furnace simply rises in proportion to the current. At the other extreme of low resistances and high currents, the voltage drop across the reactance dominates, and simply limits the current to a fixed value, so the power falls to zero as the resistance of the furnace drops to zero. Hence the characteristic curve of this type of power supply is the slightly-skewed, inverted-U-shaped curve that is sketched in Fig. 2.

When the furnace is running, each resistor will give rise to the dissipation of real power P_E , which is the electrical power that goes into generating the heat in the furnace, and is normally measured in megawatts (MW). However, the reactance will dissipate only reactive power Q , which draws no net power out of the mains. This reactive power is normally measured in MVAR to distinguish it from the real power. The total power is a combination of the real and the reactive power, and is given by the formula $\sqrt{P^2 + Q^2}$. It is measured in MVA. The power factor, commonly denoted by $\cos \phi$, is the ratio of the real power to this total power.

As furnace size is scaled up, so the resistances decrease while the reactances increase. These trends can be explained as follows:

(a) Resistance - According to the Andrae² and Kelly³ formulae, the resistance per phase R_E is related to the electrode diameter D_E by:

$$R_E = k_A / D_E \quad (6)$$

where the constant of proportionality k_A remains relatively fixed for a given process. Hence, as the furnace size increases and the electrode diameter also increases, so the resistances decrease by the reciprocal of their diameter.

(b) Reactance. - We have found that at 50 Hz the individual electrode reactance X_E in a furnace with three separate transformers and well designed bus-bars can be related approximately to the electrode diameter D_E by the following formula:

$$X_E = 0.8 + 0.2 \times D_E \quad (7)$$

(For 60 Hz, the reactances will be 1.2 times higher than the value calculated from this formula.)

As a result of these relative trends of the resistance and reactance with furnace size, the reactive power Q rises more steeply than does the real power P . Hence the power factor of the furnace decreases as the furnace size increases. A low power factor gives rise to a number of operational problems, which is why large furnaces tend to be more troublesome.

A direct consequence of having a Q that is comparable to or greater than P is that the required MVA capacity of the transformer (and of the corresponding switchgear and cables) is significantly larger than the MW power of the furnace. Figure 5 shows how this worsens as the size of the furnace increases.

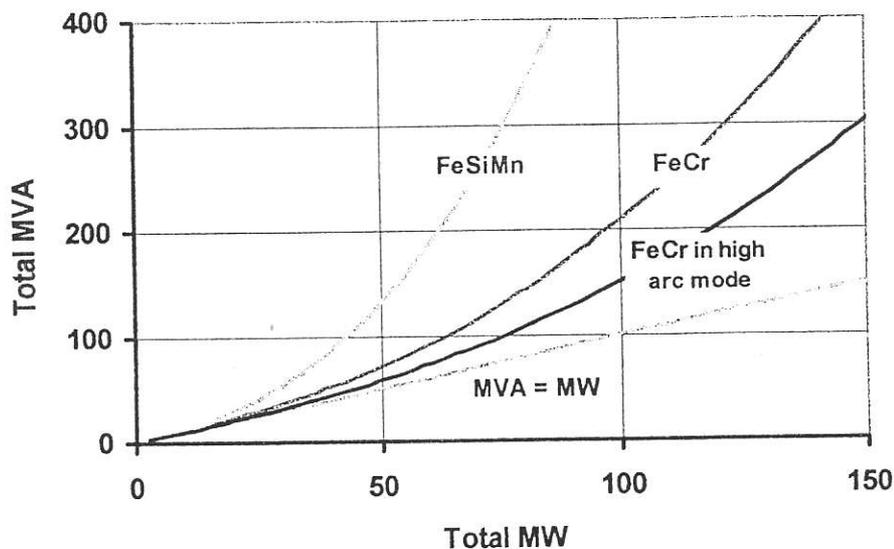


Fig. 5. Increase in transformer MVA capacity with increase in furnace power, for three different ferro-alloy processes.

Area density of power, and gas permeability of the burden

If the formula for the limiting electrode current I_E from equation (4) is substituted for the electrode current i , and the formula from equation (6) is substituted for the electrode resistance R_E in equation (1), then the following can be derived:

$$\begin{aligned}
 P_E &= i^2 \cdot R_E = [55 \times D_E^{1.5}]^2 \cdot [k_A / D_E] \\
 &= \{55^2 \times k_A\} \times D_E^2
 \end{aligned}
 \tag{8}$$

This equation (8) shows that the power dissipation is proportional to the square of the electrode diameter, and thus simply proportional to the cross-sectional area of the electrode. This indicates, inter alia, that the rate of generation of off-gas, which is roughly proportional to the power dissipation, will also be proportional to the cross-sectional area of the electrode, and hence roughly proportional to the area of the burden through which the gas must escape. This means that the gas velocities through the burden should remain fairly constant as the furnace is scaled up, which should lessen the concern that this may constrain the scale up of the process, provided a uniform gas distribution can be maintained.

However, there is always a problem with hot jets of gas that come up through blowholes in the burden periodically. The rate of generation of off-gas will rise in proportion to the power dissipation, and if this gas then all escapes through one blowhole, the heating effect will be proportionately higher. This will impose considerable heat stress on the surrounding structures and gas plant.

The interaction effect

The interaction effect is the main consequence of reactance, because it affects the actual operation of a.c. furnaces. When one electrode in a three-electrode furnace is either raised or lowered, the movement affects not only the current in that electrode, but also the currents in the other two electrodes in an unsymmetrical

way. This is the interaction effect⁷. The extent and skewness of the interaction effect increases as the power factor of the furnace decreases.

Söderberg electrodes compound this interaction problem, because they cannot be slipped at will to recover length, unlike graphite or pre-baked electrodes. In particular, if an electrode becomes short for whatever reason, then the resistance in that phase is likely to be on the high side for a period of time. This will cause not only the current in that electrode to drop, but will also affect the currents in the other two electrodes. These other electrodes will get moved to balance their currents, and in time one will grow longer while the other grows shorter. When the original short electrode eventually recovers, the shorter of the other two may become the next short electrode, and the sequence will start again. This chronic electrical imbalance will create a highly skewed power distribution inside the furnace, which may affect the metallurgical behaviour adversely.

A rough guide as to how the power factor, because of the interaction effect, affects the operability of a furnace with Söderberg electrodes is as follows:

- cos φ = 0.8 to 1.0: the interaction effect can be observed, but is not a major problem,
- cos φ = 0.65 to 0.8: the effect is significant enough to be an occasional problem,
- cos φ = 0.5 to 0.65: the effect is likely to be a continual operational problem,
- cos φ = <0.5: the effect will be a major operational problem, and the furnace may be almost unmanageable.

Because the power factor decreases as the size of the furnace increases, the interaction effect is probably one of the main constraints on building larger a.c. furnaces.

DIRECT-CURRENT (D.C.) FURNACES

Electro-magnetic inductance creates reactance only with alternating current. Hence with d.c. power, there are no constraints from the reactance side. In particular, with a multi-electrode d.c. furnace, each electrode behaves individually – i.e. there is no interaction effect.

A d.c. power supply can also be tailored to provide whatever characteristic curves are required by the furnace. Thus d.c. furnaces allow much a better control of the current, voltage and power being dissipated beneath an electrode, and, in the case of multi-electrode furnaces, each electrode can be controlled individually.

Because the voltages on adjacent electrodes in a multi-electrode furnace are similar, and the electrodes do not interact with each other operationally, they can in theory be mounted closer together, should the need arise. It is also worth noting that the flares in a multi-electrode d.c. furnace will be directed inwards, which is the opposite of the direction in an a.c. furnace.

A d.c. furnace requires a high-current connection to the hearth. Recent publications concerning the operation of open-arc d.c. furnaces have indicated that currents of up to 180 kA can be conducted from the bottom of the furnace, but these furnaces are constructed for regular hearth or anode replacement. Although the demands on the hearth anodes in submerged-arc mode are much less severe, the questions remain as to how much current can be removed from the bottom of the furnace, and how long such connections can be kept functioning. In a very large three-electrode d.c. furnace for ferro-alloys, currents of the order of half a million amps would need to be conducted out via the hearth connections.

DISCUSSION

It would seem from the above analysis that the main factor that constrains the sizes of present a.c. submerged-arc ferro-alloy furnaces is the inductive reactance caused by the magnetic fields around (mainly) the electrodes in the furnace. The main consequence of inductive reactance would seem to be the interaction effect. A second consequence is the larger transformer required. Both these consequences become more severe as the power factor decreases and they therefore become more problematical as the size of the furnace increases.

The Söderberg electrodes in larger furnaces also seem to be troublesome, but it is not clear whether this is primarily because of an inherent fragility of the larger electrodes, or because of the interaction effect, or because of the skin effect. Operation in d.c. mode would alleviate the interaction effect and the skin effect, but not the inherent electrode fragility.

With most existing submerged-arc processes, there is little that can be done about significantly increasing the resistance of the burden. However, as in the case of ferrochromium, it may be possible to change to a fully open-arc or a mixed mode of operation, thereby increasing the resistance (and therefore the voltage) significantly. In the case of ferromanganese alloys, the high vapour pressure of manganese at the normal furnace temperatures will limit the degree of arc power without incurring significant metal losses. With silicon, and ferrosilicon, the reaction between silicon monoxide and carbon requires the presence of a solid permeable burden above the reaction zone around the arc. Significantly longer a.c. arcs therefore seem to be undesirable in the silicon process. On the other hand, with ferronickel, the normal mode of operation is semi-open, and thus very high voltages are the norm. To what degree the use of d.c. power for open-arc and semi-open-arc operation will benefit these other processes has possibly not been fully evaluated.

With the correct pre-treatment of the feed materials, the permeability of the burden may not be such a constraint at higher power levels, but the furnace infrastructure will need to be able to handle the occasional hot "blow".

It is evident from the above arguments that d.c. operation could provide a way to increase the size of furnaces significantly beyond what is currently attainable with a.c. furnaces. Furthermore, it is not inconceivable that, with the use of multiple-electrode d.c. technology, ferro-alloy furnaces of well above 100 MW could be built and successfully operated.

The use of graphite or pre-baked electrodes may also help to overcome some of the problems inherent in large Söderberg electrodes, as they do not require the same level of care in their operation, and in particular they do not have to be slipped evenly and regularly.

From the viewpoint of the electricity supply grid, existing a.c. submerged-arc furnaces do not impose any major problems, apart from low power factors, which can in any case be corrected by capacitors should the need arise. Flicker is not normally a problem with submerged-arc furnaces, unlike their open-arc relatives. Furthermore, the technology for delivering a.c. power to a furnace is relatively basic, well established, and trouble free. The d.c. furnace, however, is not so simple. The types of problems created depend on the type of power supply. Thyristor bridge supplies generate severe harmonics in the waveform of the current drawn from the mains, and because of this, considerable effort has been required in the development of active and passive compensation circuits. The best solution for minimising the disturbance to the mains is the use of a chopper supply, also called a pulse-width modulation (PWM) supply, which often uses insulated-gate bipolar transistors (IGBTs). However, this type of power supply is relatively bulky, complex, expensive, and its reliability has yet to be proven.

It is also not known to what extent problems would be created by the electrical load of a very large ferro-alloy furnace on the electricity supply grid, e.g. by simply switching on or off. Could there be any transient instability problems, and would the supply authority tolerate such loads?

The production from very large furnaces relative to the total world production may become an issue if the furnaces are built significantly larger. In the case of high-carbon ferrochromium for example, the existing largest furnaces can each produce about 2% of the total world production. For larger furnaces still, the percentage would be proportionately higher.

At the peak of the characteristic curve in Fig. 2, the power factor is 0.7, while to the left of the peak the power factor is higher and to the right it is lower. Hence operation to the right of the peak of the characteristic curve is associated with large furnaces and with operational problems. Fig. 6 shows an approximate line of constant power factor, superimposed on the trend lines from Fig. 3. This line corresponds to a $\cos \phi$ of about 0.7 at 50 Hz. To the left of this line, the power factor is higher than 0.7, while to the right it is lower. That is, this line forms the approximate boundary between the problematic operating region to the right, and the more stable region to the left. This figure shows that, in general, the trends of all the processes are aiming towards the more problematic region of operation. However, the ferrosilicomanganese process is already well into this region, while the ferrochromium process still has some way to go.

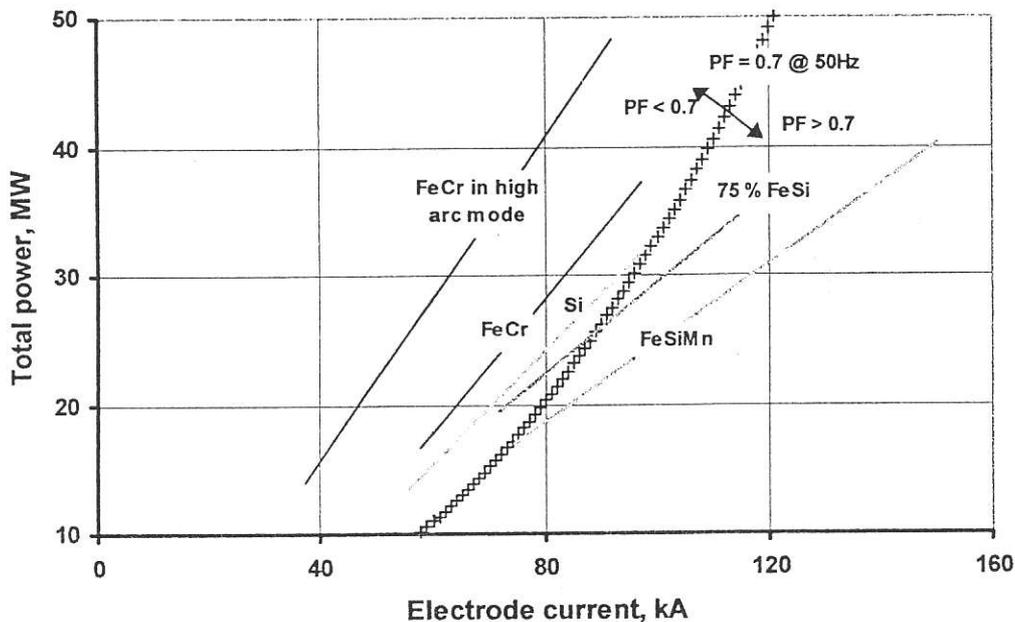


Fig. 6. A line of constant power factor, superimposed on the trend lines of Fig. 3, to indicate the approximate boundary of the problematic region of operation in a.c. furnaces.

CONCLUSIONS

Conventional submerged-arc furnaces that use a.c. mains power directly would seem to have reached or are close to a limit in size. This limit is caused primarily by the low resistance compared to the reactance in the furnace, which leads to low power factors, and this incurs operational problems that are severe enough to discourage the installation of large furnaces. There may also be a separate problem with self-baking Søderberg electrodes as they get larger, which also discourages the installation of larger furnaces. Pre-baked carbon or graphite electrodes would overcome most of the problems with Søderberg electrodes.

In recent years, power supplies have become available that can deliver d.c. power at very high currents. From the point of view of the furnace operation, d.c. obviates the problems of reactance. There is also a possibility that d.c. may lessen the problems with large Søderberg electrodes, but this remains to be proven.

While d.c. operation would seem to have relaxed some of the limits on conventional furnaces, there are still a number of questions that are unanswered, such as:

- To what extent does d.c. operation affect the mechanisms and alter the metallurgy of existing types of ferro-alloy production processes?
- Are there any restrictions on the currents that can be carried via a connection to the hearth?
- How reliable is a very large d.c. power supply likely to be?
- Very large furnaces would constitute a significant load on the electricity grid. Would this present any problems for the stability and control of the grid? Would power supply authorities tolerate such large unit loads?
- Are there any external constraints on the sizes of ferro-alloy furnaces, such as marketing and distribution of the products?
- Hot blowholes through the burden in the furnace may become an issue with significantly larger furnaces, necessitating greater attention to the control of the size characteristics of feed materials.

Summary

This paper examines the technical issues that currently constrain large-sized ferro-alloy furnaces. The possibility of further scale-up is also studied, and each of the various constraints is investigated with a view to how it might be eased or even circumvented. It would appear that d.c. power may offer some critical advantages in this regard, and may even help to relieve some of the problems that existing large furnaces display.

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