Resistance and Heat Distribution in a Submerged-arc Furnace

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by J. WESTLY* (presented by Mr Westly)

SYNOPSIS

An account is given of the electrical-resistance distribution in submerged-arc furnaces, the measurements on some eighty furnaces in one plant being compared with Andreae's, Kelly's, and Persson's experiments. Good furnace operation can be achieved if the following formula is adhered to:

$\frac{P}{I^{1,5}} = C_W$, where P is the operating load, I is the electrode current, and C_W is a constant.

This formula neglects the electrode diameter.

Heat distribution is regarded as being inversely proportional to the resistance of the furnace zones—i.e., the lower the resistance in the crater zone relative to the resistance in the furnace charge, the more power is generated in the crater zone, which aids the reaction in that zone.

The influence of over- and under-cooking is discussed. Unless one knows about the heat-generating characteristics of materials in the furnace, over-cooking is possible. Also, by adjustment of the thickness of the coke layer, a separation of burden and slag is possible in a slag process. This results in the possibility that a control on the lower zone (slag) would not influence the upper zone (burden).

In the early 1930s, F.V. Andreae[1] presented his concept of electrode periphery resistance:

$$k = R.\pi.D,$$

where k is the electrode periphery resistance,
R is the furnace operating resistance, and
D is the electrode diameter.

As the first concept relating the electrical conditions to the metallurgical conditions in the submerged-arc furnace, the Andreae formula has been extremely useful to furnace operators as well as to furnace designers.

Experience from furnace operation, however, has indicated the necessity of some correction to the Andreae formula. The first correction was proposed by Kelly[2] in 1958. He plotted the k-factor versus the power density in the electrode and gave the k-factor as a linear function of the power density. With increased furnace capacity, the power density in the electrodes increases, and, for the large furnace capacities of today, extrapolation of the correction curves proposed by Kelly gives k-factors that are too low.

At the AIME conference in 1971, Persson[3] gave the k-values as hyperbolic functions of the power density, i.e., the k-factor multiplied by the power density is a constant. This corrected formula eliminates the problem of negative resistance, which was a consequence of extreme extrapolation of the Kelly curves, and in the scaling up of furnaces it gives k-factors in better agreement with experience from large furnace units.

The correction formula proposed by Persson implies an operating resistance that is inversely proportional to the power input when the electrode diameter remains constant, and, contrary to the Andreae formula, the resistance increases proportionally to the electrode diameter at constant power input. Let us see how this compares with experience from practical furnace operation.

Figure 1 shows a diagram for a 10 MVA ferrosilicon furnace with electrodes of 900 mm diameter. Owing to restrictions in the power supply, this furnace had to be operated on reduced load for long periods every year. The best operation was obtained when the load was varied along the line A in the diagram. For comparison, the diagram also shows what the operating conditions should have been according to the other formulae discussed above.

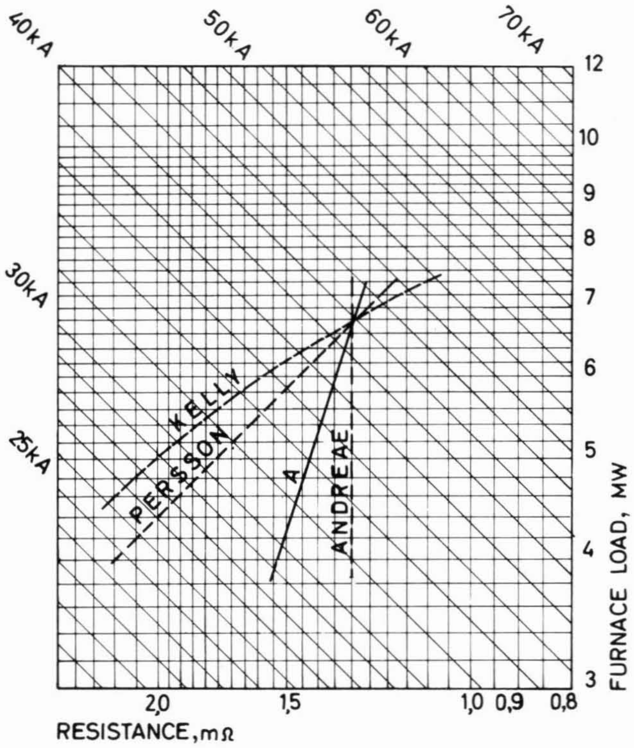

Figure 1

Operating resistance at various loads for a 10 MVA ferrosilicon furnace with electrodes of 900 mm diameter. Minimum power consumption per tonne of alloy was obtained along line A. This line corresponds to $R.P^{1/3} = const.$

Figure 2 shows the same for a 45 MVA ferrosilicon furnace. It will be noted that, for both furnaces, the best operation was obtained at a resistance (k-value) between the Andreae and the Persson formulae.

The lines of good operation in the diagram correspond to

$$k^2.i = \text{constant},$$

where

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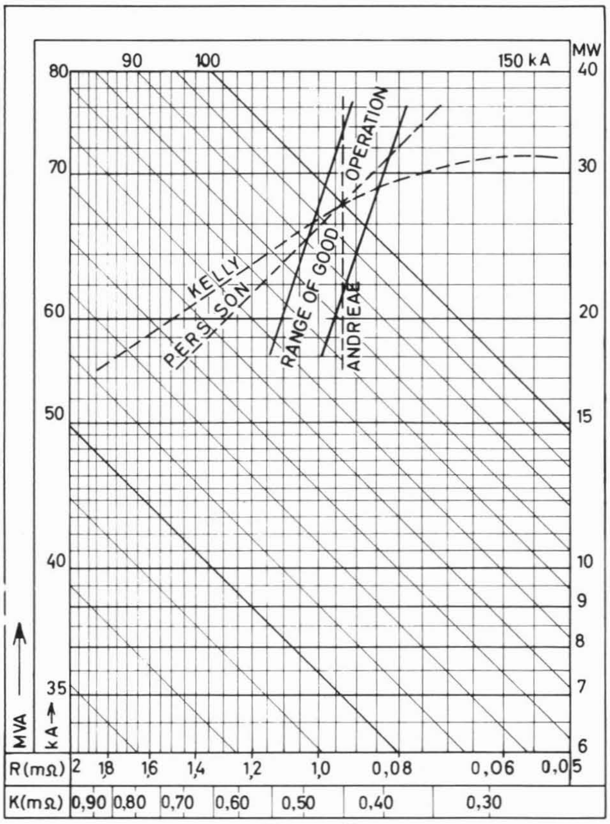

Figure 2

Operating resistance at various loads for a 45 MVA ferrosilicon furnace with electrodes of 1550 mm diameter. The range of good operation is characterized by $R.P^{1/3}$.

i is the current density in the electrodes,

or to

$$R \,.\, P^{1/3} = \text{constant},$$

or

$$I \,.\, P^{2/3} = \text{constant},$$

where

P is the power input,
R is the operating resistance,
and I is the electrode current.

Plots of the operating resistance versus the power input for various sizes of furnace operating with the same raw materials indicate that the same formula may apply in the scaling up of furnaces (Figure 3).

For a statistical check of the above formulae, they have been written in comparable forms as follows:

$$\frac{P}{I^{1,5}} = C_W,$$

where P is the operating lead,
I is the eletrode current,
C_W is a constant.

Andreae $R.\,\pi D$ = constant $P = C_A\ I^2\ D^{-1}$

Persson e = constant $D^{0,5}$ $P = C_P\ I.\ D^{0,5}$

Our formula $R\ P^{1/3}$ = constant $P = C_W.\ I^{1,5}$,

where
P is the operating load,
I is the electrode current,
D is the electrode diameter, and
C_A, C_P, and C_W are constants, which have been calculated from the available operating data.

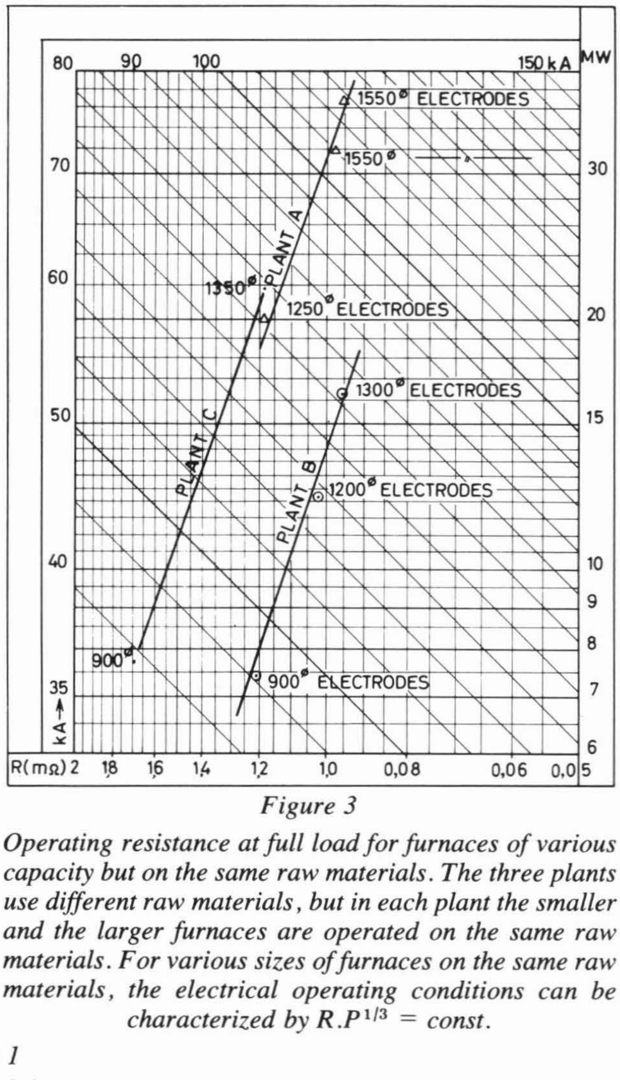

Figure 3

Operating resistance at full load for furnaces of various capacity but on the same raw materials. The three plants use different raw materials, but in each plant the smaller and the larger furnaces are operated on the same raw materials. For various sizes of furnaces on the same raw materials, the electrical operating conditions can be characterized by $R.P^{1/3}$ = const.

Table 1

The mean values of the constants

	$C_A = \frac{P.D}{I^2}$			$C_P = \frac{P}{ID}$		$C_W = \frac{P}{I^{1,5}}$	
	No. of observation	Mean value	Standard deviation	Mean value	Standard deviation	Mean value	Standard deviation
Carbide	24	1,574	±18,7%	2,541	±18,7%	3,282	±15,3%
FeSi	31	1,464	±21,7%	2,062	±17,8%	2,937	±16,0%
SiMn	13	1,323	±16,7%	1,765	±15,4%	2,600	±13,7%
FeMn	13	1,513	±15,5%	1,728	±11,1%	2,746	±13,3%
Average standard deviation			18,2%		15,8%		14,6%

Table 1 shows, for various processes, the mean value of the constants and the standard deviation in percentages of the mean value. It is found that the Persson formula gives a better approximation than the Andreae formula does; and our formula gives a slightly better approximation than the Persson formula does.

At first glance it seems surprising that a correction formula for the k-factors that eliminates the effect of the electrode diameter gives the best approximation, but in fact this formula corresponds to the Andreae formula as long as the current density in the electrode remains constant.

So far it is not contradictory to this accepted theorem, which may be deduced from the model theory if the electrode diameter is taken as representative of the linear factor, and which has been confirmed by model tests[4,5]. Before further discussion of this point, however, let us first study the principle of heat distribution. This theory, which was developed to explain the experience from ferrosilicon furnaces operated with a resistance that was too high, appears to be an important principle in submerged-arc smelting, and, as we shall see, it also explains the significance of the Andreae formula.

THE PRINCIPLE OF HEAT DISTRIBUTION

The problems experienced when a ferrosilicon furnace is operated on resistance that is too high are as follows:

(1) slag formation, which gives problems in tapping and plugging of the furnace,
(2) the electrical instruments showing little or only temporary response to the raising and lowering of the electrodes, with subsequent problems in the balancing of the furnace load and excessive electrode travel, and
(3) an abnormal wear of the electrodes, i.e., reduced wear of the electrode tip and increased wear on the side of the electrode. (Above all, wear of the slits of the fins may result in channel formation and splitting of the electrodes.)

This furnace condition, which is well known to most ferrosilicon smelters, has many names: 'slaggy' conditions, 'arcing from the leg,' and 'over-quartzed' and 'undercoked' furnace. As the two last terms indicate, the condition is frequently related to a deficiency of carbon in the mix, and in many instances this is also correct. However, it is only a secondary effect of the carbon deficiency. In a ferrosilicon furnace that is operated on a low resistance, this condition never occurs. On higher resistance, it may occur with a deficiency of carbon in the mix, but on too-high a resistance it cannot be avoided even with a surplus of carbon in the mix.

In the carbothermic reduction of ores, heat is just as essential for reduction as carbon is, and a deficiency of heat may cause incomplete reduction in the same way.

Little response of the instruments to raising and lowering of the electrodes indicates poor contact between the electrode tips and the furnace hearth, and so do the unbalanced conditions, a fact that can be explained only by appreciable deviation of the furnace hearth from neutral. The abnormal wear of the electrodes indicates that excessive current is dissipated from the electrode periphery at a high level in the furnace.

Heat generated in the unmolten charge will contribute to the melting of the raw materials, whereas the heat required for the final reduction in the depth of the furnace must be covered by the heat generation near the electrode tips.

If too much heat is consumed in the melting of the raw materials, a heat deficiency near the electrode tips may cause incomplete reduction. We can therefore define a heat distribution factor C as

$$C = \frac{Q_c}{Q} = \frac{R}{R_c},$$

where
Q is the total heat input to the furnace,
Q_c is the heat generation in the unmolten charge,
R is the furnace operating resistance, and
R_c is the resistance of the unmolten charge.

C may have values between 0 and 1. The higher the value of C, the larger the portion of the total heat input consumed in the melting of the raw materials, and the less the portion left over for reduction.

For a given set of raw materials, C is controlled by the choice of operating resistance. At too high a resistance, 'slaggy' conditions occur.

The effect of the operating resistance on the reduction is observed when frequent short-term changes are made in the operating resistance — for instance, when the resistance is changed after every tapping or for every shift without the charge composition being changed.

Figure 4 shows how aluminium and calcium in 75 per cent ferrosilicon vary with the operating resistance for a given set of raw materials.

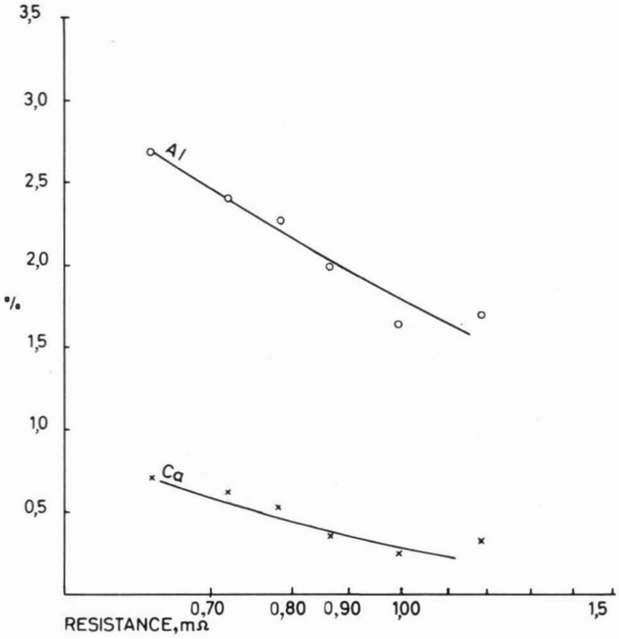

Figure 4

Average aluminium and calcium in ferrosilicon at various operating resistances

Figure 5 refers to the smelting of ferrosilicon—chromium. Silicon in the alloy and SiO_2 in the slag are plotted against the operating resistance.

Figure 6 shows how the MnO content in the ferromanganese slag varies with the resistance. Line A refers to a charge composition with approximately 800 kg of slag per tonne of ferromanganese; line B refers to the charge composition corresponding to approximately 330 kg of slag per tonne of ferromanganese. It is interesting to note that the displacement of the lines along the R-axis corresponds very well with the change in the charge resistance,

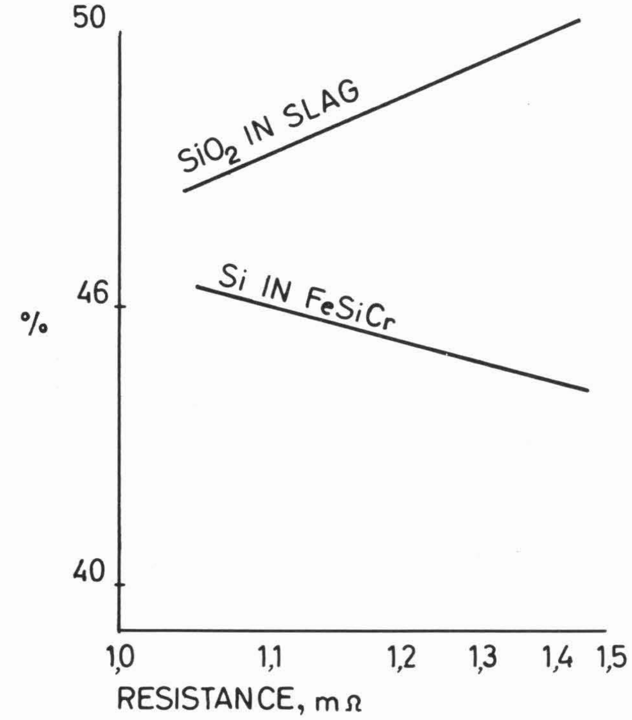

Figure 5

Average Si in SiCr and SiO_2 in SiCr slag at frequent changes in operating resistance

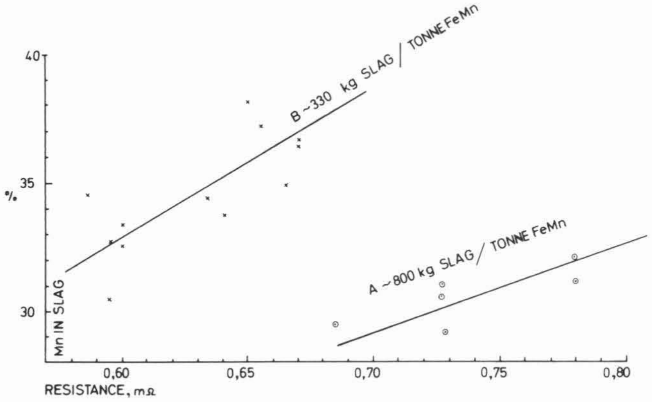

Figure 6

Mn content of FeMn slag at short-term variations in operating resistance without changes in charge composition

which should be expected from the different coke volumes in the mix.

It is accepted thinking among furnace operators that the heat distribution is controlled by the penetration of the electrodes. As the operating resistance is controlled by the electrode penetration, what is then the difference?

The difference is that, even with deep electrode penetration, slagging occurs if the resistance between the electrode tip and the furnace hearth is too high. For instance, when a ferrosilicon furnace suddenly gets an 'undercoked' mix, the electrode penetration increases. When the electrode reaches the low-limit switch or if it is held back on manual operation to avoid too deep a penetration, the resistance will increase and slag will be formed in spite of the deep penetration.

THE SIGNIFICANCE OF THE ANDREAE FORMULA

The principle of heat distribution gives the operating resistance as a product of the heat distribution factor and the resistance in the unmolten charge components, i.e.,

$$R = C\,.\,R_c.$$

How can we expect R to vary with the physical dimensions of the furnace?

$$\mathrm{d}R_c = \frac{\rho\,.\,\mathrm{d}x}{2\pi\,\times.\,h}.$$

Integrating from the electrode periphery $\left(\frac{D}{2}\right)$ to a constant ratio $\left(\frac{a}{2}\right)$ of the electrode spacing (s) gives

$$R_c = \frac{\rho}{2\pi h}\cdot\,\ln\frac{as}{D}.$$

$$R = C\,\frac{\rho}{2\pi h}\ln\frac{as}{D}.$$

Only the electrode diameter has no influence on the resistance as long as the ratio between the electrode diameter and the electrode spacing remains constant. The electrode diameter in the Andreae formula has been replaced by the electrode penetration. In correct scaling up of furnaces, the linear dimensions of electrode spacing, crucible diameter, and crucible depth are proportional to the third root of the power input, and so also is the electrode diameter, provided that the current density in the electrodes is kept constant. As long as all the linear dimensions are proportional, it does not matter which one we use in our formula for the resistance. They may all be replaced by the third root of the power input, i.e.

$$R.P^{1/3} = \text{constant},$$

provided that the heat distribution (C) and specific charge resistance (ρ) are constant. This is the same relation as was found empirically (see page 122).

THE COKE LAYER

The principle of heat distribution presupposes a separation between the reaction zone and the charge zone. Without this separation, the temperature of the reaction zone should be determined by the melting-point of the raw materials. And processes that require temperatures above the melting-point of the raw materials should not be possible.

In ferrosilicon furnaces, the separation is provided by the formation of a crater at the electrode tip. Experiments in a small model furnace show that, if the charge is pushed down into the crater by frequent poking, only slag and hardly any metal are produced.

In slag processes, as, for instance, the smelting of ferromanganese, silicomanganese, ferrochromium, silicochromium, and pig iron, the coke layer should provide a separation between the unmolten raw material and the liquid slag. It is therefore essential for the coke layer to be adjusted to a suitable thickness by correct sizing of the coke. Too small sizing of the coke will result in a thin coke layer, which makes the operation very delicate or even impossible owing to inadequate separation. Too large sizing of the coke gives a low resistance, hot furnace gases low in CO_2, and high power consumption.

It would be interesting to discuss other aspects of the coke layer — for instance, electrical and thermal conductivity. In this paper, however, where heat distribution is the main topic, we just want to stress the importance of the coke layer as a separating medium between the melting zone and the reaction zone, because in many processes the separation is a prerequisite for a proper heat control.

CONCLUSION

A study of the available operating data indicates that the formula

$$R \, . \, P^{1/3} = \text{constant},$$

which is the same as

$$I/P^{2/3} = \text{constant},$$

gives the best approximation to actual operating data. The formula seems to apply in the scaling up of furnaces as well as in the operation of a particular furnace on various loads.

In the scaling up of a furnace, the formula is a consequence of the linear dimension being proportional to the square root of the power input.

In the operation of particular furnaces on various loads, changes in furnace load will change the temperature in the electrodes and the surrounding charge, with a subsequent change in the charge resistance. It may be no more than coincidence that the same formula gives a good approximation also to these changes in resistance.

The principle of heat distribution explains the significance of the operating resistance and how it affects the reduction. We have seen how it affects the formation of Al and Ca in ferrosilicon furnaces and thereby the slag formation. It also explains some problems that are not uncommon in the production of ferromanganese, pig iron, silicochromium, etc.

Consider a furnace that is operated on a constant resistance and in which the degree of reduction is controlled by control of the fixed carbon in the mix. This method of operation works well as long as the heat-distribution factor is adequate. But, if there is a change in the charge resistance for some reason or other (for instance, a change in the sizing or in the conductivity of the coke) without any change in the fixed-carbon content, then the heat distribution factor will change, with a subsequent change in product analysis. If these changes are corrected for, not by a change in operating resistance but by adjustment of the fixed carbon in the mix, the carbon balance will be upset.

In silicochromium smelting, for instance, increased charge resistance, which gives a lower heat-distribution factor, will give a higher silicon content in the alloy and less SiO_2 in the slag. If this is corrected for by a reduction of the fixed carbon in the mix, the furnaces will be undercoked.

Decreased charge resistance, i.e. a lower heat-distribution factor, gives less silicon in the alloy and more SiO_2 in the slag. If the fixed carbon in the mix is increased to increase the reduction of the silica, the furnace will be overcoked.

In the operation of submerged-arc furnaces, a proper control of the heat-distribution factor is as essential as control of the fixed carbon.

Whereas the importance of a correct carbon balance is realized fully, control of the heat-distribution factor has frequently been neglected. Problems related to the heat distribution have in many instances been wrongly interpreted as problems in the control of the fixed carbon.

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DISCUSSION

Dr R.C. Urquhart[*]*:*

I wonder whether drawing a straight line through the three points in Figure 3 is a little presumptuous? Would you expect a point included, e.g., 48 MVA or higher furnaces, to fall on this line?

Mr J. Westly:

The largest furnace referred to in Figure 3 is actually a 48 MVA furnace. An even larger furnace is now in operation in the same plant, and the best operation is achieved on line A.

The number of observations referred to in Figure 3 has been considered too few for a statistical analysis, and unfortunately we have not sufficient data from furnaces using the same raw materials for such an analysis. The statistical check referred to in Table 1 therefore comprises furnaces with great variations in raw materials.

However, it is interesting to compare the results with the dimensional analysis presented by Böckman[4]. Provided that there is electrical and geometrical similarity in model and prototype, the heat generation in corresponding points will be the same, i.e., the same heat distribution when the voltage is directly proportional to the linear dimension and the electrode current is proportional to the square of the linear dimension. It then follows that the power input should be proportional to the third power of the linear dimension, and the operating resistance inversely proportional to the linear dimension; and hence

$$\mathrm{I} \sim P^{2/3}$$

or $RP^{1/3}$ = constant, which is the empirical equation indicated by Figure 3.

Mr S.G. King[†]*:*

The differences in the various formulae suggest that smelting furnace design is still more an art than a science. Do you agree?

Mr Westly:

I agree that the operation as well as the design of electric smelting furnaces is very much a matter of experience. Many points still remain to be explained scientifically.

Mr S. Selmer-Olsen[‡]*:*

Is the thickness of the coke-layer or 'coke-bed' process self-dependent, or does it depend upon resistance distribution in the furnace, coke reactivity, secondary voltage, etc.?

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[‡] Amcor Management Services (Pty) Ltd, South Africa.

Mr Westly:

The thickness of the coke layer must depend on how fast the coke is consumed in the furnace. Sizing and reactivity of the coke, oxygen potential, and temperature conditions are therefore factors that one would expect to influence the thickness of the coke layer. Advocating a relation between electrical conditions and temperature conditions, I should also expect the electrical conditions to have some influence on the thickness of the coke layer.

Mr G.M. Mansfield:*

(1) In older furnaces with less sophisticated instrumentation, how does one measure or calculate the operating resistance?

(2) In South Africa it is sometimes the practice, in order to get furnaces to operate effectively, to include wood chips in the charge. How are the heat and power distribution affected?

Mr Westly:

(1) The operating resistance may, for instance, be calculated from the power input and the electrode current, as

$$R = \frac{P}{I^2},$$

where P = active power per electrode in kW,
I = electrode current in kA, and
R = operating resistance in mΩ.

If there are no meters for the electrode current, which is frequently the case with old furnaces, the electrode current can be calculated from the primary-current readings.

(2) Wood chips will increase the charge resistance (R_c). If the operating resistance (R) is kept constant, the heat distribution factor

$$C = \frac{R}{R_c}$$

will be reduced, i.e., more heat will be generated below the tip of the electrode and less in the charge. If the operating resistance is increased proportionally to R_c, the heat distribution will be the same.

Dr A.J. Eve†:

Can you give the values of your constants for high-carbon (4 to 6%) ferrochromium?

Mr Westly:

Using the formula $I = cP^{2/3}$ applied to a three-electrode furnace,

where I = current per electrode in kA and
P = total furnace load in MW,

the constant c in the smelting of high-carbon ferrochromium varies from 6 to 11, with most of the furnace in the range 7 to 9. The lower values of the constant are from furnaces operated on Rhodesian chromium ores.

Mr M. Sciarone‡:

In your model, the resistance is related to raw materials only. Do you think this is a limitation to your model, or do other factors, such as slag layer in the furnace and electrode spacing, influence the operating resistance? Would you comment especially on the slag layer?

Mr Westly:

According to the model that gives the operating resistance as the heat-distribution factor multiplied by the charge resistance, one should not expect the thickness of the slag layer to affect the operating resistance. Experience from ferromanganese furnaces in which the thickness of the slag layer has been increased by tapping of slag from a separate slag tap-hole from 60 to 100 cm above the metal tap-hole also confirms that it makes no difference to the operating resistance.

Regarding electrode spacing, one should expect increased electrode spacing to increase the value of R_c and, subsequently, also the operating resistance. I have tried this in a ferrosilicon furnace without much success and without any significant improvement in the operating resistance.

Downing and Urban have studied the relation between resistance and electrode spacing. If we calculate the expected increase in resistance for furnaces with normal electrode spacings, we find that an approximately 17 per cent increase in the electrode centre-to-centre distance is required to give only 5 per cent increase in resistance. Such a a large increase in electrode spacing will adversely affect the furnace operation in other ways; and most likely one will only find that separate craters surrounded by rather conductive material are formed around the electrodes, having an adverse effect on the operating resistance.

Dr R.C. Urquhart:*

In Figure 6, furnace resistance increases with MnO content in the slag. However, the resistivity of this slag will decrease with increased MnO content. Does this mean that the slag resistivity is of less importance regarding electrical conduction in the furnace than the position of the electrodes in the burden?

Mr Westly:

As the variations in MnO content illustrated in Figure 6 are a result of changes made in the operating resistance, I would rather say that the MnO content of the slag varies with the operating resistance, that is, when the charge resistance is kept constant. With increased charge resistance, the same MnO content is obtained with a higher operating resistance. Note the difference between lines A and B, where line A represents the mix with the higher charge resistance.

The resistivity of the slag is not expected to affect the operating resistance in processes where the reduction may suffer if too large a fraction of the power input is consumed in the melting of raw materials. In a matte furnace, however, this is not the case, and in matte smelting there is a very good correlation between slag resistance and operating resistance.

Mr D.I. Ossin:*

Figure 6 indicates that the slag makes a large contribution to the furnace resistance in ferromanganese production. Have you similar data for ferrochromium production, and, in view of the data in Figure 6, do you consider that an increase in slag resistance will improve the process?

Mr Westly:

The difference in line A with a mix giving 800 kg of slag, and line B with a mix giving 300 kg of slag, per tonne of alloy is explained by the difference in charge resistance R_c (the higher coke density and the higher conductivity of mix B). It is not the volume of liquid slag in the furnaces that makes the difference. As a matter of fact, during test A, slag and metal were tapped through the same tap-hole, whereas in test B the slag was tapped separately from a tap-hole 60 cm above the metal tap-

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*Ferralloys Ltd, South Africa.
†Rio Tinto, Rhodesia.
‡Metalloys Ltd, South Africa.

*National Institute for Metallurgy, South Africa hole, i.e., the volume of liquid slag in the furnace was larger during test B than during test A.

I do not have similar data from ferrochromium production; but the same principle certainly applies in ferrochromium smelting, and I do not expect increased slag resistance to improve the operating resistance.

Dr K.G. Willand:*

(1) What does 'Changing the resistance without changing the charge composition' mean? Did you change the particle size or the pitch diameter?

(2) How is it possible to change the resistance after every tapping?

(3) Do you think that the heat-distribution factor is also applicable to charge chromium and 4 to 6 per cent ferrochromium furnaces in such a way? Tests we have done show that a higher resistance leads to a higher silicon content in ferrochromium and an overheating of metal and slag.

Mr Westly:

(1) The resistance in the various levels of the furnace interior determines the current paths and the heat generation in the various parts of the furnace. The pattern is certainly complicated, but some useful conclusions can be arrived at by a simplification of the pattern to two shunt resistances:

R_c – accounting for a heat generation contributing to melting of the raw materials above the coke layer, and

R_R – accounting for a heat generation that will give the required temperature rise in the lower levels of the furnaces and cover the heat requirement for the chemical reactions.

To avoid too many complications, I have ignored the resistance in the electrodes, bus tubes, etc., and called the total furnace resistance for the operating resistance R. In fact, this is the same resistance that Andreae and others call the 'arc resistance', a name I have tried to avoid because it may be misleading.

(2) The relation between these resistances is the well-known

$$\frac{1}{R}=\frac{1}{R_C}+\frac{1}{R_R}.$$

R_c is determined by the resistivity of the charge and the geometry of the furnace; but the electrode position has only little or not effect on R_c.

R_R, however, which is the resistance between the electrode tip and the metal bath, is highly sensitive to changes in electrode position. By raising and lowering of the electrodes, we can adjust the R_R and thereby the operating resistance R.

(3) The theory of heat distribution also applies to ferrochromium smelting.

If by a higher resistance you mean a higher R_c, which your first question may indicate, your experience confirms the theory. If by a higher resistance you mean a higher R, your experience apparently contradicts the theory. However, with an inadequate thickness of the coke layer (i.e., too small sizing of the coke), I have found that the increased stirring effect, which is a result of the lower operating resistance, carries the coke away from the electrodes. The slag makes contact with the unmolten charge components and loses temperature. You may have had the same experience, though the other way round.

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