Continuous melting of metallised ore pellets

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Detailed analyses of the final reduction heat transfer processes involved in the continuous melting of DRI particles in the electric arc furnace are essential for the optimization of the design and operating characteristics of the furnaces.

Both the rate of production and the properties of steel may be greatly influenced by variables such as:

- the physical and chemical properties of the charge
- the capacity and the dimensions of the furnace
- the method of charging and the rate of feeding of the charge
- the position of the feeders and the nature of the distribution of the charge in the hot liquid phases.

A simple computer model has been developed for the heating and melting of single metallised pellets which may be ingested into the molten phases of the electric arc furnaces. The model is based on the results of several experimental studies on the heating and melting of stationary and spinning spherical particles in pools of hot molten slags.

From the model, the residence time of the pellets floating in and passing through he layer of slag covering the molten bath of the hot metal in an electric furnace can be approximately determined. The approximate nature of the results is due to the lack of information on the thermal properties of the materials at the high operating temperatures of arc furnaces. These properties have been extracted from the generalized forms of the thermodynamic correlations available[2, 4] at present.

In this paper, a slightly modified version of the earlier computer model[2, 3] is used to test the applicability of the model to some interesting industrial problems. The time taken for 90% of the floating DRI pellets to melt is determined for several cases. From the results, the rate of production of steel from continuous charges of the metallized pellets into a 3-phase arc electric furnace is calculated.

Single pellets in an arc bath

Because of their relatively low density, the direct reduced iron pellets normally used in electric steelmaking cannot enter the molten metal phase until they have fully melted. However, they may be trapped at the slag-metal interface, or be entrained in the liquid slag phase.

Although the melting process of the individual DRI pellets at the slag-metal interface may occur more conveniently, the utilisation of the relatively dense pellets which may fall directly into the slag-metal interface has the disadvantage of reducing the temperature of the hot metal. For this reason and because of the possible rapid melting of the metallised pellets held-up in actively boiling slags, only the melting of pellets floating in the liquid steelmaking slags is considered in the following analysis.

Immediately after being dived, the DRI particles are surrounded with a crust of slag which freezes pn their surface and warms the particles up. This temperature rise inside the particles causes the carbon to react with the residual oxygen forming a mixture of CO and CO_2 which evolves from the particles and mixes the slag. A large degree of mixing results in a greater rate of heat exchange and a greater rate of evolution of gas.

Removing oxygen and carbon from the particles changes their density, porosity, heat capacity, thermal conductivity, heat of fusion and the temperatures at which melting will begin and end. Heat consumption by the reduction reactions slows down the temperature rise of the particles, resulting in a less uniform temperature distribution inside them. The crust of solidified slag will melt away as the surface temperature of the particles becomes high enough to prevent the transmission of all the heat provided to the particles into their core. Gas evolution from the particles helps the removal of the crust both by simulating heat transmission into the particles and by pumping away the cold mushy layer of slag that may exist at the solid-liquid interface.

Experiments and results

Several tests were devised to study the heating and melting of the metallised particles in the electric furnace. By heating DRI materials in sealed containers the evolution of gas could be investigated with the help of an integrating flowmeter.[1,4] Heat exchange between the particles and the surrounding slag was studied by hanging a DRI pellet from a steel nipple with a piece of steel wire and submerging it into a pot of molten slag. Measurements were made of the temperature rise at the centre of the pellet and the thickness of the skull that solidified on the pellet[1,2,4] was determined.

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Several types of commercially manufactured DRI pellet and lump ore materials were employed for the gas evolution and the heat transfer studies. An example of the evolution results obtained for a low carbon sample that was partly oxidised during a long storage period is shown in Figure 1. The most favourable thermodynamic and kinetic conditions available to the oxygen-carbon reduction reactions results in the occurrence of peaks at temperatures of about 700 and 950°C. It appears that the former is due to the decrease of the oxidation level of the oxides contained in the sample to 2, while the latter is due to the fall of that level to zero.[2]

An example of the effects of the evolution of gas on the growth of the slag skull on immersed nickel spheres[1] (radius = 9 mm) is shown in Figure 2. Nitrogen was forced through two small ports (0.3 mm radius) made in the lower portion of the specimens to simulate the evolution of gas. As is seen, this shifts the growth curve to the lower thicknesses, the shifted curve being almost parallel to the curve for no gas evolution.

Changes in the microstructure of the DRI materials and the temperatures at which these changes occur have a substantial effect on the thermophysical properties and the melting rate of the DRI materials. Using the binary iron-carbon phase diagram and the evolution results the temperatures at which these changes occur were estimated and then verified by thermal analysis of the metallised materials in an experimental set-up (see Fig. 3). A comparison is drawn between the phase transformation temperatures estimated from the evolution results and those measured by the differential thermal analysis of the DRI materials in Table 1. As indicated by the consistency of the data, the transformation temperatures can be approximated from the binary iron-carbon phase diagram.

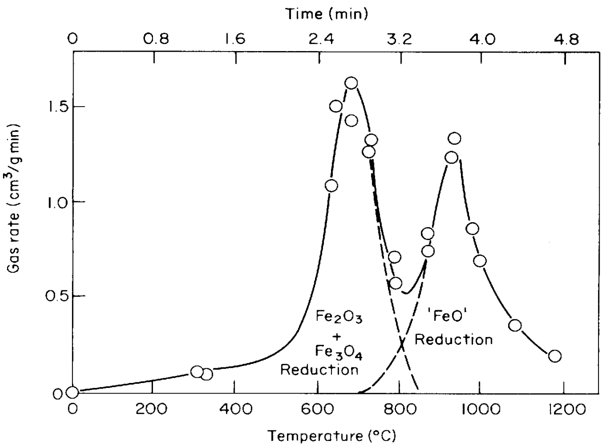

Fig 1. Rate of evolution of gas from metallised pellet materials heated at 250°C/min. %O = 2.55; %C = 0.93; particle size = 1 mm

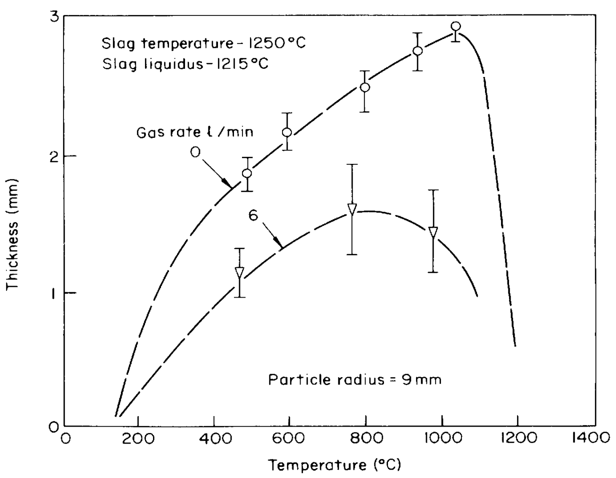

Fig 2. Effect of evolution of gas on growth of slag skull

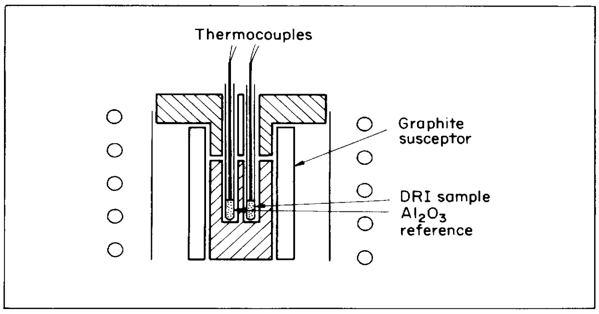

Fig 3. Assembly for differential thermal analysis of DRI materials

Table 1. Transformation temperatures of DRI materials as determined from gas evolution results and by DTA measurements.

	Pellet				*Lump ore*	
Phase	*DTA*	*GE*	*DTA*	*GE*	*DTA*	*GE*
$C \rightarrow \underline{C}$	720	727	729	727	723	727
γ	960	957	–	943	777	787
$\gamma + \delta$	–	1494	1449	1457	1403	1398
$\gamma \rightarrow \ell + \delta$	–	1500	1488	1500	–	–
$\delta \rightarrow \ell$	–	1526	1516	1510	1524	1535

Melting rate of pellets

Steel is produced from DRI materials charged into an electric furnace at a rate determined by the feeding rate and the iron content of the metallised charge. Even if the arcs can produce excessively large quantities of heat the rate of feeding cannot exceed the rate of melting of the DRI pellets. Thermal interaction between the cold particles when their actual charging rate exceeds the maximum permissible feeding rate reduces the Nusselt quantity of the bath and decreases the rate of melting of the charge even further. Continued excessive charging of the solids may cause the pellets to freeze into solid islands of extremely low melting rate.

Calculations of the maximum rate of feeding of the DRI pellets to the furnace can be made for ideal melting conditions. In this case the pellets can be considered as thermally isolated spherical particles uniformly distributed inside a bulk liquid slag of constant temperature, T_{∞}. When floating in the slag, the particles must remain at least several times the thickness of the thermal boundary layer apart in order to avoid a decrease in the heat transfer coefficient and the effective bulk temperature of the slag.

By utilising the results of the tests described in the previous section the melting time of the non-interacting DRI pellets floating in the electric-arc bath can be calculated. It may be assumed that the pellets remain spherical and that their density and porosity do not substantially change, but that their radii gradually decrease as they melt.

Simplifying the general heat conduction equation and its boundary conditions to those of a one dimensional heat flow leads to the following set of equations:[3,4]

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r} = \frac{1}{\alpha}\frac{\partial T}{\partial t}\right) \tag{1}$$

$$T = Tm, \qquad r = L \tag{2}$$

$$Nu(T_\infty - Tm) = 2L\frac{k}{k_s}\left(\frac{\partial T}{\partial r}\right)_{L^-} - \frac{\Delta Hm \cdot \rho}{k_s}\frac{\partial}{\partial t}(L^2) \tag{3}$$

$$k_s\left(\frac{\partial T}{\partial r}\right)_{R^+} = k\rho\left(\frac{\partial T}{\partial r}\right)_{R^-}, \qquad r = R \tag{4}$$

$$T = T_\infty, \qquad r = \infty \tag{5}$$

$$\frac{\partial T}{\partial r} = 0, \qquad r = 0 \tag{6}$$

where T, t and r are temperature, time and distance from the centre of the immersed pellet, T_∞ is the temperature of the bulk slag, Nu is the Nusselt quantity of the slag, L is the distance of the solid-liquid interface from the centre of the pellet, R is the initial radius of the pellet, k_s and kp are the thermal conductivities of the slag and the pellet and α, k, ρ, ΔHm and Tm are thermal diffusivity, thermal conductivity, density, heat of fusion and melting temperature of (a) the pellet when $L \leqslant R$ and (b) the solid slag when $L > R$.

Converting the partial derivatives to finite difference ratios results in a set of finite-difference equations that yields both the future temperature of the spherical shell elements along the radius of the particle, Ti, j+1, and the position of the solid-liquid interface, Lj+1, at a time Δt after the present time t=j. Δt as are stated in the following equations:

$$\begin{aligned} Ti, j+1 = Ti, j + \alpha^2\frac{\Delta t}{\Delta r}\cdot\frac{Ai}{Vi}(Ti+1, j - Ti, j) \\ + \frac{\Delta t}{\Delta r}\cdot\frac{Ai-1}{Vi-1}(Ti-1, j - Ti, j) \end{aligned} \tag{7}$$

$$\begin{aligned} Lj+1 = Lj + \frac{k}{\rho \cdot \Delta Hm}\cdot\frac{\Delta t}{\ell j}(Ti-1, j - T_\ell) \\ + \frac{k_s \cdot Nu}{2L \cdot \Delta Hm \cdot \rho}\Delta t\,(T_\infty - T_\ell) \end{aligned} \tag{8}$$

Here, Ai and Vi are the mean area and the mean volume of the element i. The value of ℓj is chosen to be less than Δr and is employed to indicate the movement of the interface within an element:

$$Lj = i \cdot \Delta r + \ell j \tag{9}$$

At time $t = j \cdot \Delta t$ the melted fraction of the pellet can be determined from the following equation:

$$Fm = 1 - (Lj/R)^3 \tag{10}$$

The volume of the gas evolved from the pellet is computed from the following equation:

$$Vg = 4\pi\int_0^R \upsilon_g \cdot \rho_p \cdot r^2\,dr \tag{11}$$

in which the specific gas volume υ_g is a function of the temperature of the DRI and is determined from the evolution results described in the previous section. Equation (11) allows the calculation of the changes in the chemical composition and the thermal properties of the pellet as it is heated.[2,4] Employing a high speed computer to simultaneously solve Equations (7) to (11) allows the determination of the time that is necessary for the pellet to melt in a hot bath of molten material with a known Nusselt quantity.

Of all the data available on the effect of the stirring on the Nusselt quantity of the fluids, the correlation suggested by Levins and Glastonbury[9] (which is consistent with the results of Brian, Hales and Sherwood[7]) is selected to calculate the Nusselt number of the slag when agitated with the gases expanding and rising in the slag:

$$Nu = 2 + 0.83\left(\frac{\epsilon^{1/3}L^{4/3}}{\upsilon}\right)^{0.62} Pr^{0.36} \tag{12}$$

In the above equation υ and Pr are the effective kinematic viscosity and the Prandtl quantity of the slag. ϵ is the rate of dissipation of energy by rising gas bubbles per unit mass of the slag and is calculated from the following:[10]

$$\epsilon = 2ER'T_\infty \ln\left(1 + \frac{\rho_s gh}{Pa}\right) \tag{13}$$

E is the rate of evolution of gas per unit mass of the slag, T_∞ is the temperature of the bulk liquid slag, H and ρ_s are the height and the density of the slag, g is the gravitational constant, R′ is the gas constant and Pa is the atmospheric pressure.

If the distance between the particles becomes so short that the pellets may thermally interact, the correlation given by Calderbank[11] can be used for determination of the Nusselt quantity of the slag:

$$Nu = 2 + 0.26\left(\frac{\epsilon L^4}{\upsilon^3}\right)^{1/4} Pr^{1/3} \tag{14}$$

A comparison of Equations (12) and (14) indicates that the effect of the agitation of the liquid slag by rising gas bubbles on the coefficient of the transfer of heat in the slag greatly decreases when the slag is excessively charged with the cold DRI pellets. As a result of the dramatic rise of the viscosity of the slag when embedding a large quantity of solid particles the Nusselt number of the bath and the melting rate of the pellets decrease even further.

Considering a cylindrical element of the liquid slag the total mass of the accumulated particles can be calculated as follows for a simple-cubic arrangement of the particles:

$$\Gamma = \frac{\pi}{6}\rho_p\left(\frac{Nu}{n + Nu}\right)^3 a \cdot h \tag{15}$$

where ρ_p is the density of the DRI pellets and the separation factor n indicates the distance between the immersed particles. The rate of accumulation of the solids in the liquid is equal to the difference between the rate of feeding and the rate of melting of the pellets. Ideally, the total quantity of the pellets accumulated in the liquid equals the maximum permissible mass of the solids that can be imbedded in the slag.

At the steady state where the rates of feeding and melting are the same, the quantity of the pellets floating in the slag is equal to the product of the feeding rate of the pellets and their melting time. Therefore the maximum feeding rate can be obtained by (a) maximising the permissible amount of the cold charge that can be embedded in the slag without jeopardising the ideal thermal condition of the bath as a medium for heating the single isolated pellets and

(b) minimising the melting time of the entrained DRI pellets.

A combination of the melting time of the DRI pellets with the total mass of the charge that can be accumulated in the slag will lead to the ideal rate of feeding of the DRI charge to the electric furnace:

$$\dot{f}_l = \frac{\pi}{6}\rho_p\left(\frac{Nu}{n + Nu}\right)^3 \frac{a \cdot h}{t_m} \tag{16}$$

The separation factor n does not remain the same throughout the liquid slag. At the areas close to the arcs where the transmission of heat to the liquid is more conveniently accomplished the specific mass of the solids per unit volume of the liquid can be greater. On the contrary at the regions far from the arcs, a larger separation factor should be employed in order to avoid any increase in the melting time of the pellets which could be caused by multipellet interactions.

For an ideal charging operation in which the DRI pellets are evenly distributed throughout the slag, h and a are equal to the height and the area of the surface of the slag. In normal electric furnace operation, however, they have smaller values. For simplicity they will be taken as the total height of the slag and that portion of the surface area which may be covered with the charged pellets.

If the final reduction of the metallised charge is the only source of formation of gas and the partial pressures of CO_2 and CO in the gas are p and (1 – p) the rate of evolution of gas per unit mass of the slag can be calculated from the following equation:

$$E = \left(\frac{X_O - X_{O,s}}{M_O(1 + p)}\right)\left(\frac{\dot{f}}{\rho_s \cdot a \cdot h}\right) \tag{17}$$

where X_O is the weight fraction of oxygen in the DRI, $X_{O,s}$ is the portion of X_O which transfers to the slag and Mo is the atomic mass of oxygen. If the slag phase is only made of gangue and FeO, the rate of production of steel from a 100% DRI charge can be determined from the following expression:

$$\dot{P} = \left(X_{Fe} - \frac{M_{Fe}}{M_{FeO}} \cdot \frac{\%\,FeO}{100\text{-}\%\,FeO} \cdot X_G\right)\dot{f} \tag{18}$$

X_{Fe} is the weight fraction of iron in the DRI and M_{Fe} is the atomic mass of iron.

Practical applications

It is feasible to use the computer model to determine the effects of both the furnace design and the specifications of the DRI particles on the melting time of the metallised pellets entrained in an electric-arc bath. From this the ideal rate of production of steel from a continuous charge of such pellets may be calculated. Some examples are described in the following sections. A separation factor of 10 is used here and the average diameter of the segment of the liquid in which the pellets are embedded is assumed equal to one third of the total internal diameter of the hearth. Some of the important specifications of the furnace and materials utilised in the calculations are given in Tables 2 and 3.

Table 2. Specifications of the arc furnace.

Hearth diameter (m)	6
Production rate (tph)	50
Slag height (cm)	25
Slag temperature (°C)	1600

Table 3. Properties of materials.

Slag density (g/cm^3)	2.9
Conductivity of solid slag (cal/cm.sec.°C)	0.0028
Conductivity of liquid slag (cal/cm.sec.°C)	0.0032
Kinematic viscosity of slag (cm^2/sec)	1.72
FeO content of slag (%)	22
Radius of pellets (cm)	0.75
Density of pellets (g/cm^3)	2.68
Chemical composition of pellets (%):	
iron	87.38
oxygen	4.00
carbon	2.83
gangue	5.79

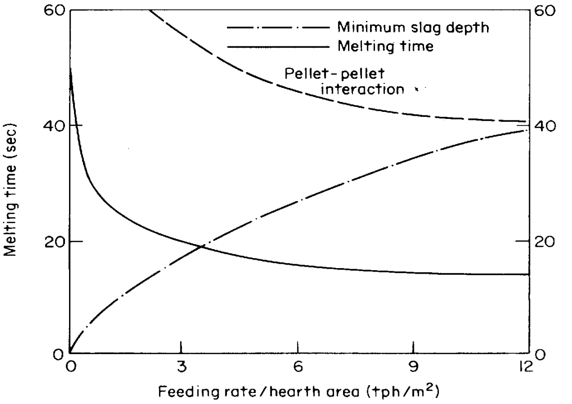

Fig 4. Effect of electric furnace design on the melting time of continuously charged DRI pellets

Design of furnace

Both the melting time and the feeding rate of the DRI pellets are functions of the design of the electric furnace. In Figure 4, the effect of the variation of the ratio of the DRI feeding rate to the area of the surface of the slag on the melting time of the immersed pellets is illustrated. Also shown is the minimum depth of the slag needed to conveniently embed the charge without any multipellet interactions. If the depth of the slag falls below the minimum depth shown, the melting time of the pellets may jump to the extremely high melting times demonstrated by the broken line.

When the feeding rate of the pellet rises to about 2.5 tph/m^2 the evolution of gas in the slag causes a substantial decrease in the melting time of the pellets.

Above that rate, however, the effect of the variation of the ratio of the feeding rate to the hearth area on the melting time of the pellets becomes less significant, provided the depth of the slag remains greater than the required minimum.

Due to the slight decrease in the rate of dissipation of energy by the ascending gases, the melting time of the pellets increases with the height of the slag. However, as is demonstrated in Figure 5, this effect is not significant. Since larger quantities of the DRI pellets can be embedded in slags of greater depth, the rate of production of steel from such pellets will increase as the height of the slag becomes larger. Note that the production of steel from the melting of any pellets that may be trapped at the slag-metal interface is not considered in this analysis. This is

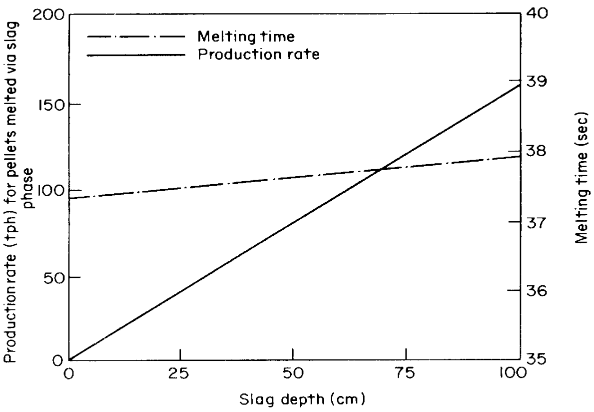

Fig 5. Effect of depth of slag on the melting time of DRI pellets immersed in liquid slag and on the rate of production of steel from them

because the normal transmission of a large quantity of the heat from the arcs into the slag makes it more desirable to operate the furnace in such a way that the majority of the pellets melt when floating in the liquid slag phase.

A deep pool of slag with highly dense pellets is also beneficial because it shows the falling pellets and partially heats them before they arrive at the slag-metal interface. In their slow descent, the retarded pellets reduce the population of the particles trapped at the interface. This decreases the possibility of multi-pellet interactions in that region. In addition to the benefits described above, a deep layer of slag also protects the walls and roof of the furnace and reduces the extent to which the refractory is consumed during a normal arc-furnace operation. Detailed description of these advantages are given in the literature.[12]

Appropriate selection of the densities of the pellets allows them to be distributed uniformly throughout the slag. At the regions close to the arcs where the direction of the motion of the fluid is upward, feeds of higher density may more conveniently sink and melt in the slag. Since the average density of both the immersed particles and the slag changes as the gases evolve, the position and the motion of the pellets can not be easily determined. An empirical correlation can however assist the steelmaker in conveniently selecting the appropriate range of the densities of the DRI pellets for the most uniform distribution of the charge throughout the slag.

Properties of the slag

According to the measurements made by Fine, Engh and Elliott,[6] the thermal conductivity of molten slags containing more than 10% FeO do not differ materially with the composition of the slags.[13] Thermal conductivities of a variety of compositions of hot oxides have been measured by Nauman, Foo and Elliott[5] and have been found to be in the range of 0.003 to 0.008 cal/cm . sec . °C. As is illustrated in Figure 6, the melting time of the DRI pellets falls to less than one half as the thermal conductivity of the slag varies within this range. Figure 7 shows that the steel productivity grows almost linearly with the thermal conductivity of the slag in the above range.

Liquid slag viscosity is greatly influenced by chemical composition and temperature. Variations in slag viscosity in the range of 1 to 5 poise (normal steelmaking range) substantially affect both the life-time of the ingested pellets and the rate of production of steel from such pellets (Figures 6 and 7). A dramatic increase in the viscosity of the liquid slag may be brought about by the presence of sinking solid particles (DRI pellets) and the presence of gas bubbles as a separate phase or dispersed as a froth.[14,15]

This in turn will cause a substantial drop in the productivity of the process. Above about 4 poise, the effect of the rise of the viscosity becomes less significant (Figure 10). Because of their large viscosity neither highly acidic nor highly basic slags are desirable. From the melting point of view, a self-fluxed charge of pellets that can produce a neutral slag of relatively low viscosity may be the most advantageous.

The net effect of the rise of the Nusselt quantity of the slag and the internal resistance of the particles to the transfer of heat is an increase in the melting time of the pellets and a decrease in the productivity of the process

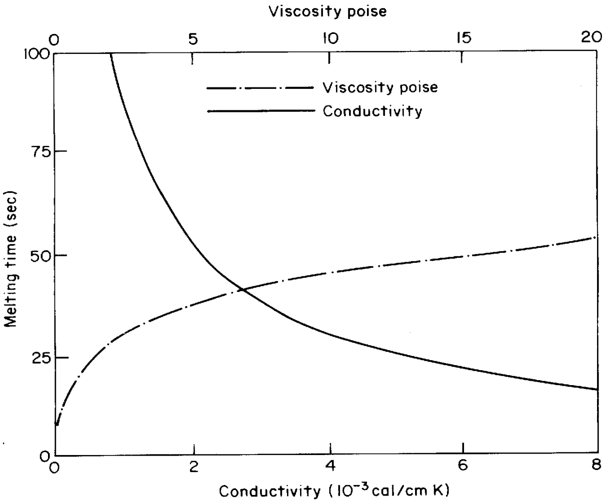

Fig 6. Effects of thermal conductivity and viscosity of hot liquid slags on the melting time of DRI pellets

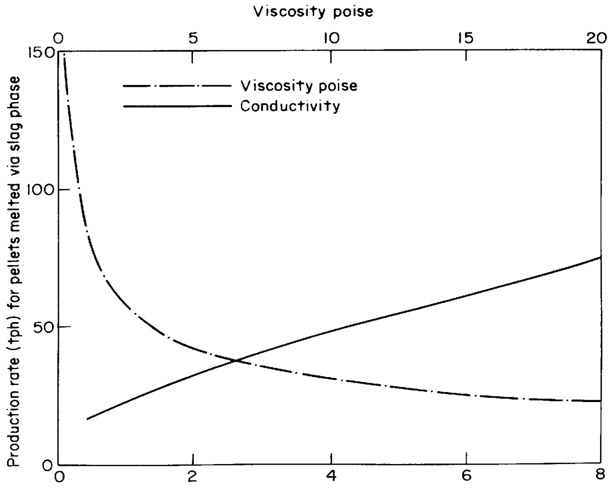

Fig 7. Effects of thermal conductivity and viscosity of hot liquid slags on the rate of production of steel from DRI pellets

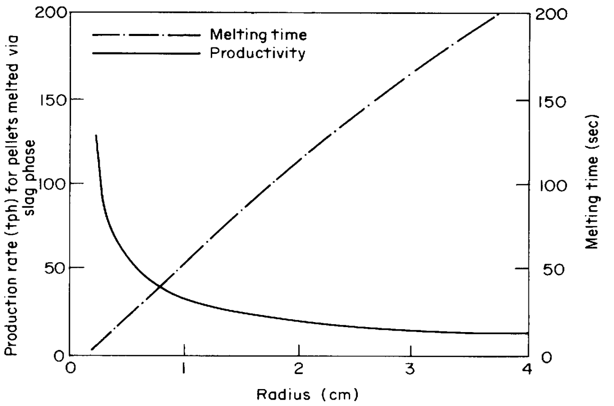

Fig 8. Effect of radius of DRI pellets on their melting time and on steel productivity in an electric arc furnace

as the radius of the DRI pellets increases (Figure 8). When the diameter of the pellets exceeds about 2 cm, however, the effect on steel productivity is relatively small. In spite of the practical difficulties, it is therefore desirable to design a continuous feeding operation in which the iron-rich fines can be directly melted in the electric-arc bath.

Summary of results

Experimental and theoretical studies on the essential characteristics of the melting of the DRI pellets in steelmaking slags have indicated that the productivity of DRI electric steelmaking can be enhanced by:

- increasing the feeding rate of the charge enough to produce an extremely active slag but not so much that the floating DRI pellets may thermally interact
- increasing the 'hold up' capacity of the liquid slag by increasing its volume
- increasing the size of the furnace while maintaining the temperature of the liquid slag uniform and sufficiently high to avoid the formation of 'islands' or aggregates of cold pellets by increasing the arc power
- utilisation of combinations of raw materials that can produce a liquid slag which may possess as low a viscosity as possible and as high a thermal conductivity as possible
- development of new processes for utilisation of finer DRI particles as a continuous feed of the electric arc furnace.

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