

The melting rate of DRI pellets in steelmaking slags

K. Sadrnezhad and J. F. Elliott

A comprehensive understanding of the behaviour of DRI pellets when charged into steelmaking slags is necessary to optimise both the design of the electric arc furnace and the physico-chemical properties of the pellets, the aim being to produce more efficient furnace operation. To aid investigators, a simple computer model has been developed which can determine gas evolution rates, slag shell growth on pellets and temperature and composition variations within the pellets. This article gives the latest results obtained with the model.

The problems associated with the heating and melting of prerduced iron particles in steelmaking slags have been studied extensively.¹⁻⁴ Results of the previous investigations made on transfer of heat from liquid slag to the immersed pellets, evolution of gas from the pellets when heated in a sealed bomb, and the mathematical calculations made of the melting time of the spherical particles in typical steelmaking slags have been described earlier.⁴ Results of further studies are given in this article.

An inclusive dynamic model is an apparatus for combining the effects of all influential parameters to predict the behaviour of the DRI pellets when charged into the steelmaking furnace. Elliott and Nauman² developed a model for heating an inert spherical particle immersed in a liquid slag. They translated Fournier's law of heat conduction and the dominant boundary conditions to finite difference equations and solved them by a step-by-step numerical method. From the model, the melting rates of spherical particles in hot ferrous-silicate slags have been estimated for a number of simplified conditions.^{3,4}

Because of heat transfer from liquid slag to a cold immersed pellet, a layer of slag may freeze at the periphery of the pellet which will remelt later.²⁻⁴ The thickness of this layer is a function of many variables such as time, temperature of the slag, initial temperature of the pellet, properties of the slag and of the pellet, and the motion of the slag relative to the pellet. The variation of the thickness of the frozen slag layer on a spherical particle has been computed, based on the difference of the heat which is transferred from the liquid into the surface of the solid and that which is conducted from the surface of the solid to the cold core.² The thickness of the shell varies on the surface of the pellet, becoming thicker as the distance from an active bubbling site increases.⁴

Dr Sadrnezhad is assistant Professor of Metallurgy, Isfahan University of Technology, Iran. He was formerly a post-doctoral associate at the Massachusetts Institute of Technology, USA.

Professor Elliott is Professor of Metallurgy at the Massachusetts Institute of Technology.

Precise knowledge of the properties of the solid and liquid slag and of the DRI pellets is essential in determining the behaviour of directly reduced pellets when charged into steelmaking slags. These properties may appreciably change as the pellets are heated in a steelmaking furnace. In the work reported here, the computer model developed earlier is modified for such changes and is used to evaluate the melting time of DRI pellets heated in an electric furnace. The heat transfer and gas evolution processes are analysed separately. The results are then synthesised by means of the appropriate interrelations. Simple experimental tests are designed to collect the information that is essential to building and testing the model. The model can be used to determine the parameters that are influential in optimization of the DRI-electric arc steelmaking practice.

Experimental details

Commercially produced DRI pellets of different sources were heated in a small experimental furnace (Fig 1) containing induction melted metallurgical slags of varying chemical compositions (Table 1)^{3,4}. The rates of gas formation and the temperature rise at the centre of the pellets were measured for comparison with the model calculations. Observations made of the solidification of liquid slag on the periphery of the immersed DRI pellets showed that at moderate rates of gas evolution (1 l/min for a 2 cm pellet) a number of active bubbling sites appeared on the surface of the frozen shell, so allowing the evolution of gas from the pellet into the slag. At relatively high gas rates (3 l/min for a 2-cm pellet) the slag shell was porous and permitted the evolution of gas from almost all of its surface.

Cast nickel spheres of 18 and 30 mm diameters, with two and three 0.5-mm diameter ports in their lower part were used to simulate the effects of gas evolution on the heat-rate transfer and on the thickness of the slag shell that froze when the particles were immersed in the molten slag.⁴ The spheres were submerged in a liquid slag bath while a flow of nitrogen was forced through their gas ports. They were later withdrawn from the slag and measurements made⁴ to determine the thickness of the slag shell that formed on them.

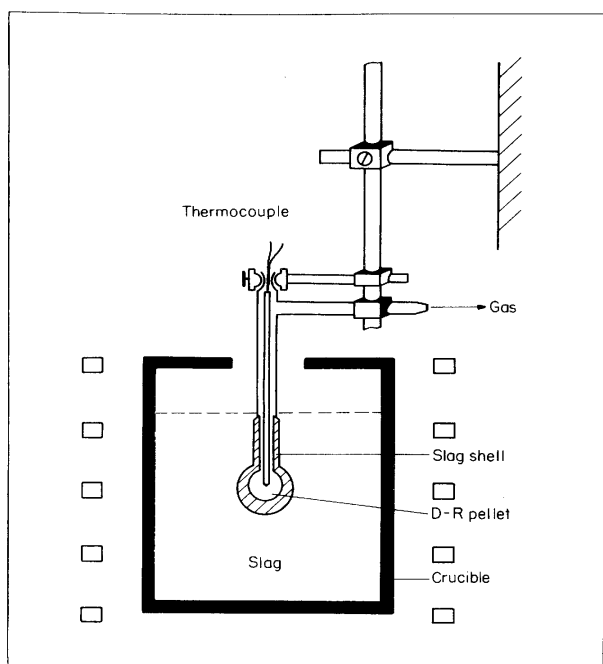


Fig 1. Experimental furnace for heat transfer studies

Table 1. Chemical composition of slags.^{3,4}

Component	Weight %		
	A	B	C*
Fe Total	48.0	35.0	11.0
"FeO"	60.5	40.5	14.2
Fe ₂ O ₃	1.4	5.0	—
SiO ₂	38.1	40.5	31.4
CaO	—	7.0	31.4
Al ₂ O ₃	—	5.0	12.5
MgO	—	1.0	10.5
S	—	1.0	—

*Synthetic Steelmaking Slag

Crushed samples of DRI pellets were also heated in a cylindrical steel bomb similar to one used in earlier experiments,⁴ and the evolution rate and chemical composition of the gases evolved were measured. The total volume of the gas was determined from the data on the rate curves and the chemical composition of the gas. The rate of temperature increase at the centre of the samples was varied from 50 to 1000°C/min. This rate was maintained constant during an extraction test by adjusting the rate at which the inductive heat was supplied to the bomb.

Three examples of the rate of gas evolution from a 90% metallised sample manufactured by Hyl are illustrated in Fig 2 for different rates of temperature rise at the centre of the charge. Similar results for a 93% metallised sample manufactured by Midrex are shown in Fig 3. The shift of the smaller peaks towards the left (i.e. lower temperatures) when the rate of rise of the centre-temperature is increased is due to non-uniform temperature distributions produced in the samples at the relatively high heating rates. The effect of the non-uniform temperature profile on the total volume of the gases evolved from an Hyl sample is illustrated in Fig 4. At rates below 250°C/min, however, because of the relatively uniform temperature distribution

produced in the sample, the effect of the rate of centre-temperature increase on gas evolution is not significant. This is illustrated in Fig 5.

Numerous measurements made on the evolution of gas from the various DRI samples show that the total volume of the gases evolved depends, principally, on the chemical composition of the pellets. The effect of the size of the particles on gas evolution is insignificant. Some of these results are summarized in Fig 6, in which the total volumes of the gases evolved per gram of DRI, and the balanced content of carbon that is necessary for release of these volumes are plotted against the degree of metallisation of DRI for different particle temperatures.

The compositions of the gases evolved from a series of DRI samples held at a constant temperature or heated at the rate of 250°C/min are illustrated in Fig 7. The principal components of the gas are carbon monoxide and carbon dioxide with less than 1 cm³/g-DRI water vapour for samples held at constant temperature, and an undetectable amount

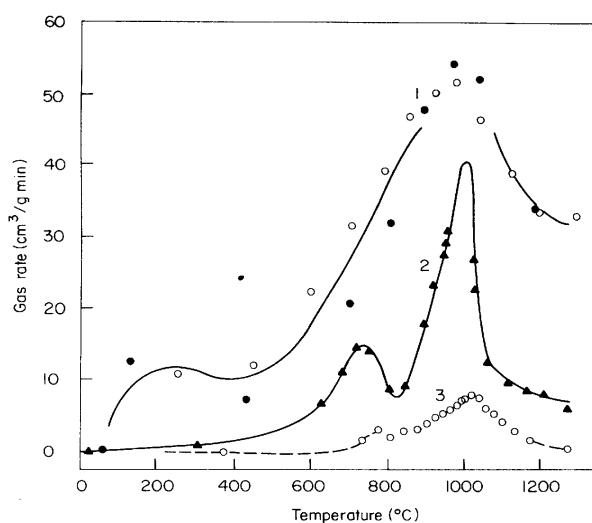


Fig 2. Gas evolution from Hyl pellets. Notation: line 1, 3.28%O, 2.21%C, particle size 1 mm, rate of temperature rise 1000°C/min; line 2, 3.28%O, 2.21%C, 1 mm, 250°C/min; line 3, 3.24%O, 2.21%C, 2 mm, 50°C/min

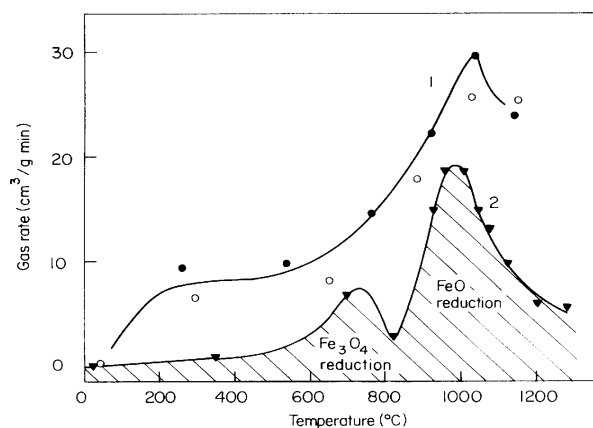


Fig 3. Evolution of gas from Midrex pellets as a result of magnetite and wustite reductions. Notation: rate of temperature rise 1000°C/min (line 1), 250°C/min (line 2), 1 mm particle size, 1.99%O, 1.78%C

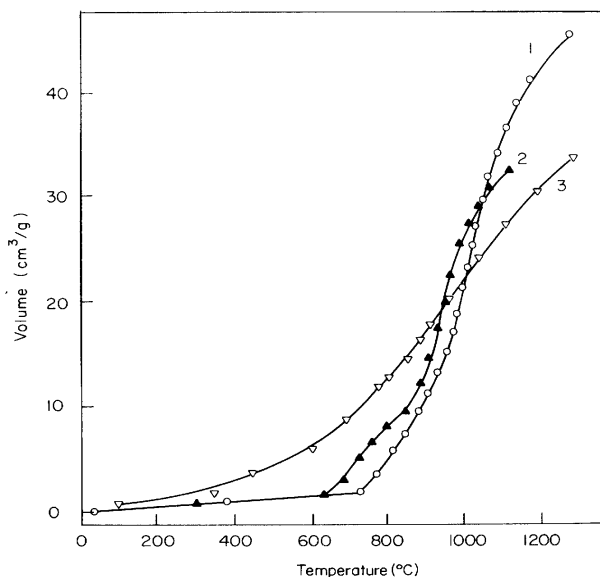


Fig 4. Effect of non uniform temperature distributions produced at high heating rates on evolution of gas from Hyl pellets. Notation: line 1, 3.24%O, 2.21%C, particle size 2 mm, rate of temperature rise 50°C/min; (line 2), 3.28%O, 2.21%C, 1 mm, 250°C/min; (line 3), 3.28%O, 2.21%C, 1 mm, 1000°C/min

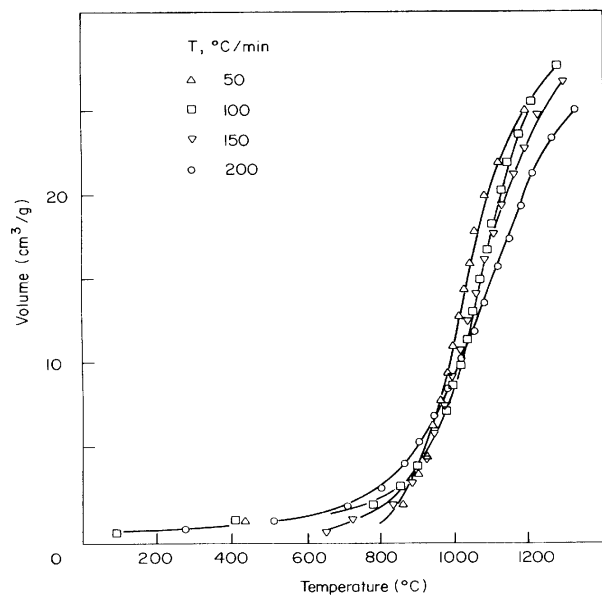


Fig 5. Evolution of gas from Hyl pellets heated at 50, 100, 150 and 250°C/min (see key). Particle size 2 mm, 2.01%O, 1.06%C

of water ($\pm 0.1 \text{ cm}^3/\text{g-DRI}$) for samples heated at 250°C/min. Above 650°C, the concentration of water vapour is less than 0.1 and can be neglected.

A simple calculation of the stoichiometric volumes of the gases evolved from various samples indicates that the reduction of magnetite to wustite is responsible for the appearance of the first peak in the rate curves at about 750°C. Also completion of the $\text{Fe}_3\text{O}_4/\text{FeO}$ conversion is

responsible for the minimum occurring at about 820°C (Fig 3). Using the data given in Fig 7, the stoichiometric gas volumes can be determined from the following reactions:

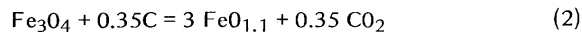
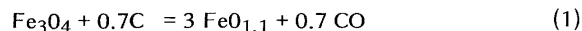


Table 2 provides a comparison of the calculated and measured volumes of the gases evolved from various DRI samples when heated to 820°C in a bomb. As can be seen, the data are fairly consistent. The carbon can be present in the DRI samples as carbide, free graphite or dissolved in the iron. Dissociation of carbide can also lead to the formation of free or dissolved carbon:



Above 750°C, although the conversion of magnetite to wustite is favoured by high temperatures, the rate of gas evolution decreases due to the decrease in the Fe_3O_4 content.

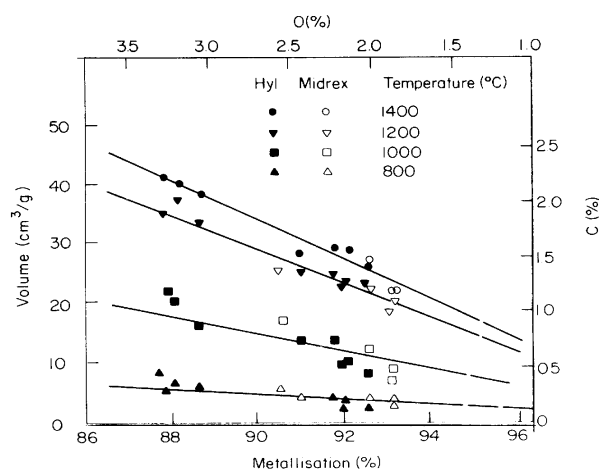


Fig 6. Gas evolution from Midrex and Hyl pellets. Rate of temperature rise, 250°C/min

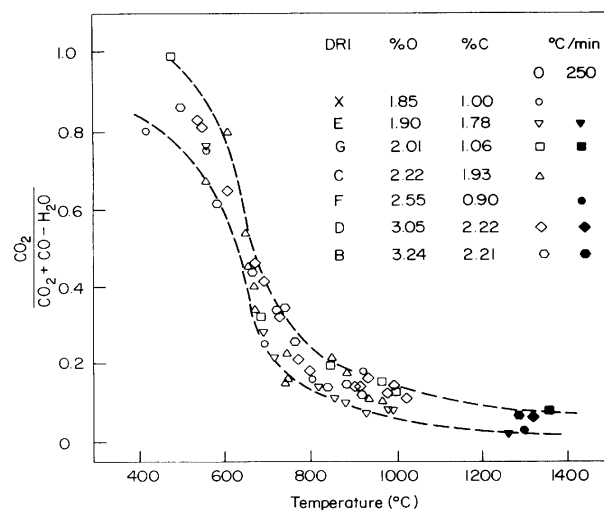


Fig 7. The concentration of CO_2 in the gases evolved from DRI materials held at constant temperature or heated at 250°C/min. Above 650°C, the concentration of H_2O is less than 0.1. Notation: E, G, C, F, D, B, DRI produced from pellets; X, DRI produced from lump ore

Table 2. Stoichiometric and measured gas volumes evolved from DRI when heated up to 820°C.

DR Material	Type	Size (mm)	Oxygen (%)	Gas Volume (cm ³ /g)	
				Stoichiometry	Measured
Midrex Lump Ore	—	1	1.85	4.1	4.8
Midrex Pellets	E	2	1.87	4.2	4.6
Midrex Pellets	E	1	1.99	4.4	4.6
HYL Pellets	C	2	2.14	4.7	4.7
HYL Pellets	C	1	2.22	4.9	4.7
HYL Pellets	H	1	2.43	5.4	5.3
HYL Pellets	D	1	3.19	7.1	7.3
HYL Pellets	B	2	3.24	7.2	7.0
HYL Pellets	B	1	3.23	7.3	8.9

The relatively rapid reduction of wustite to iron according to Eq 4, 5 results in the appearance of another peak in the rate curves at about 1000°C. Above this temperature the rate of gas evolution decreases with increasing progress of the reactions and the removal of the last traces of oxygen or carbon from the DRI



Modelling

The evolution of gas from DRI pellets immersed in a liquid slag produces several results; change of the character of the fluid; change of the Nusselt number of the slag, thinning of the slag shell that may freeze on the pellets, variation of the thermo-physical properties of the pellets and of the slag. Based on a number of simplifying assumptions, these changes are determined from the information available in existing literature and the results of simple laboratory measurements. The results are utilised in simulation of the mathematical model for heating and melting of DRI pellets in steelmaking slags.

Gas Evolution from a Pellet

In Fig 8, a DRI pellet immersed in a liquid slag is divided into spherical shells of finite thickness Δr . The distribution of temperature in and out of the pellet is determined by solving the heat conduction equation in spherical coordinates numerically.² The total volume of gas that evolves from the pellet is computed by summing the volumes of the gases evolved from various shells. Based on the data given in Fig 6 (and for simplicity) it may be assumed that the volume of the gases evolved is proportional to the oxygen content of the pellet provided that there is sufficient carbon for complete reduction of the iron oxide constituents. Use of a known gas evolution pattern allows computation of the volumes of the gases that evolve from various shells at finite time intervals and the continuation of the calculations on an iterative basis.

Heating Character of the Slag

Since the difference between the temperature of the bulk slag and that of the solid/liquid interface for a pellet with the solid slag shell is constant, the flow of heat to the surface of the solid is controlled by the heat transfer coefficient of the bath. The flow of heat from the interface to the cold core is, however, determined from the inward temperature gradient and the thermal conductivity of the solid shell; the latter being influenced by the porosity and the pore diameter of the shell. Heat transfer from the liquid slag to the pellet is considered in more detail in the appendix.

Thinning of the Slag Shell

Measurements made of the thickness of the slag layer that freezes on an immersed sphere show that the evolution of gas leads to localised thinning of the slag shell around a gas port and a decrease in the average thickness of the shell. The measurements indicate that the thinning ends shortly after immersion of the specimen when the root of the shell is solidified. Gas evolved from the particle sweeps the freezing islands of slag from around the gas ports and results in

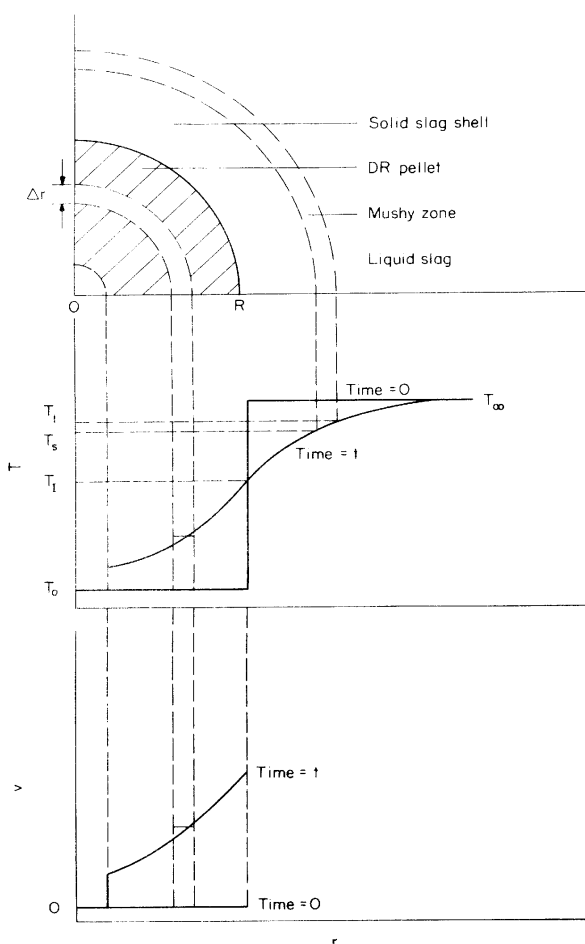


Fig 8. Distribution of temperature and gas volume for a DR pellet immersed in liquid slag

the decrease of shell thickness during the thinning period (Fig 9).

Properties of Materials

The effective thermal conductivities of DRI pellets and porous slags are calculated from the geometric mean of the thermal conductivities of the constituents and the pores.¹⁰

$$k_e = \sqrt[n]{\prod_{i=1}^n k_i \psi_i} \quad (6)$$

where k_i and ψ_i are the thermal conductivity and the volume fraction of the constituents or the pores. The pellets contain iron, carbon, iron carbide, magnetite, wustite, gangue and dissolved carbon. The volume fraction of each phase was assumed to be proportional to its weight fraction:

$$\psi_j = W_j (1 - \psi_p) \quad (7)$$

where ψ_j and W_j are the volume fraction and the weight fraction of the constituents and ψ_p is the volume fraction of the pores.

The heat of fusion of the pellets is estimated from the heats of fusion of their components. The overall specific heat of the DRI pellets is calculated based on the contribution of the following items:

1. specific heats of the constituents,
2. enthalpies of the reduction reactions occurring during heating of the pellets,
3. heat of transformation of cementite to austenite.

The reduction reactions are endothermic but the decomposition of cementite is slightly exothermic, as is illustrated in Table 3.

Results and Discussion

In Fig 10, a comparison is made of the calculated and measured rises in the centre-temperature of a 94% metallised Midrex pellet (line a) and a fully metallised Midrex pellet (line b), both immersed in a hot bath of slag. Below 300°C, because of the higher thermal conductivity and lower specific heat of the totally reduced pellet, the rate of temperature rise at the centre of the fully reduced pellet

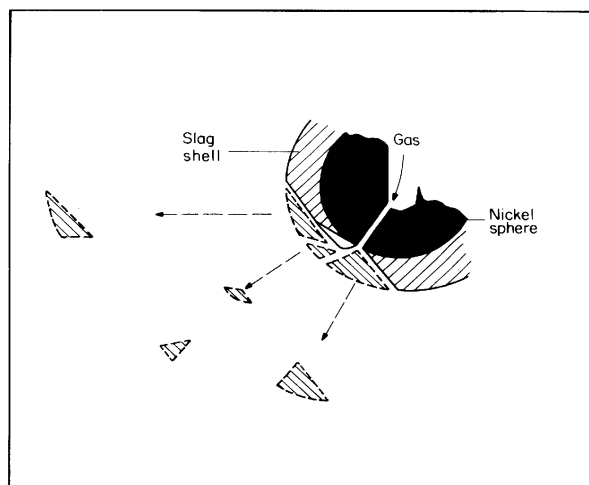


Fig 9. Physical model for removal of slag shell by evolving gas

Table 3. Enthalpies associated with reduction reactions and phase transformation in DRI pellets.¹¹

Conversion	Temp., °C	ΔH
Magnetite → Wustite	727	1.89 cal/cm ³ – GAS
Cementite → Austenite	727	–1.23 cal/g – Fe ₃ C
Wustite → Iron	1000	1.35 cal/cm ³ – GAS

(line b) is greater than that of the non-reduced one (line a). Above that temperature, however, because of the mixing generated in the slag by evolving gas bubbles, the non-reduced pellet is heated more rapidly. Yet, the centre-temperature of the fully metallised pellet remains greater.

When a cold pellet is plunged into a hot bath of slag, the temperature at its surface rises rapidly. However, because of the relatively low thermal conductivity of the pellet its core remains cold. A relatively large volume of hot gas may thus form at the areas close to the periphery of the pellet. This gas will heat up the cold core if sucked into the supporting tube for measurement of its evolution rate (cf, Fig 1). The convective heating of the core causes the initial discrepancy of the measured volumes from the calculated ones shown in Fig 11.

The effect of the evolution into the slag of gas from a submerged spherical object (radius=1.5 cm) on the growth of the shell of slag on the particle is demonstrated in Fig 12 in which the measured and the calculated shell thicknesses are compared.

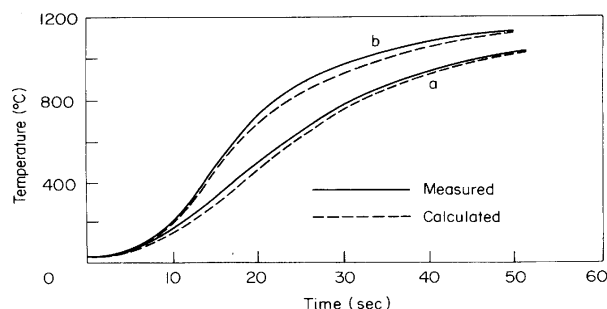


Fig 10. Temperature rise at the centre of a Midrex pellet immersed in slag A. Notation: (a) 1.99%O, 1.78%C; (b) totally reduced with hydrogen. Slag temperature, 1235°C

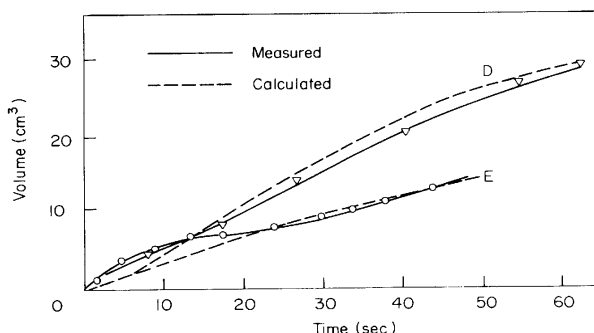


Fig 11. Gas evolution from a Midrex (line E) and an Hyl (line D) pellet heated in slag B. Notation: (D) 3.19%O, 2.22%C; (E) 1.99%O, 1.78%C. Slag temperature, 1250°C

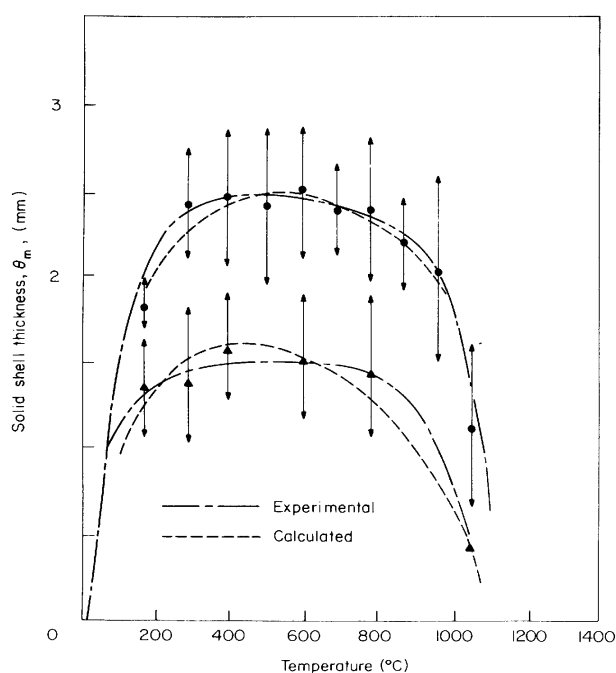


Fig 12. Growth of the shell of solid slag on a nickel sphere (radius, 1.5 cm) immersed in slag B. Notation: growth rate, 6000 cm³/min (upper pair of lines), 0 cm³/min (lower pair). Slag temperature, 1275°C

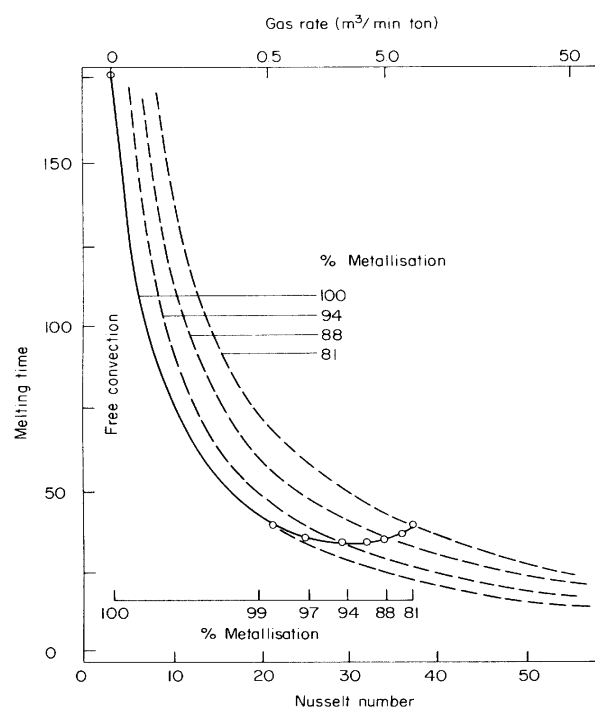


Fig 13. Melting time of DRI pellets in a steelmaking slag stirred with gas bubbles. Specifications of pellets and furnace are given in Tables 4 and 5. Slag temperature, 1600°C

The effect of the Nusselt number of the slag on the total melting time of DRI pellets of various metallisation levels is illustrated in Fig 13. The specifications of the pellets are summarized in Table 4. As is shown in Fig 13, pellet melting times are substantially less with an agitated slag than for a slag at rest. The relative insensitivity of the melting rate to the Nusselt number of the bath at high levels of mixing is due to the excessive rise of temperature at the surface of the pellets which decreases the difference between the temperature of the bulk and that at the surface of the pellets.

Assuming that the evolution of gas from DRI pellets is the only source of agitation, the Nusselt number of the liquid slag produced from continuous melting of the pellets specified in Table 4 in a 25-t arc furnace with the specifications given in Table 5 can be calculated from Eq 12 (appendix). The quantity of lime added to the furnace is assumed equal to the gangue content of the pellets so that the basicity of the slag remains unity. Effects of the degree of metallisation of the DRI pellets of Table 4 on their melting time is also demonstrated in Fig 13. It can be seen that although the maximum melting rate occurs at a metallisation level of about 94%, the effect of the variation of the degree of metallisation of the pellets in a range between 88 to 97% on the melting rate of the pellets is not appreciable. It is to be noted that this range depends on the specifications of the furnace and of the charged pellets. Because of the dramatic decrease in the melting temperature of the DRI pellets containing an excessive quantity of carbon, the melting rate of such pellets is expected to be greater than that of the pellets containing a balanced content of carbon.

The melting time of the DRI pellets increases faster than their diameter. For each 5% increase in the gangue content (Al₂O₃, SiO₂) the melting rate of DRI pellets of the same size and the same iron/oxygen/carbon ratios decreases up to about 7%. The melting rate of DRI pellets increases dramatically when their density exceeds that of the slag. This is because of the tendency of such pellets to pass rapidly to the slag/metal interface where melting can be completely rapidly.⁴ Pellets of high density are not necessarily desirable, however, because of difficulties in maintaining the temperature of the metal bath well above the melting temperature of the pellets. This is especially true when a large quantity of cold DRI descends to the slag metal interface immediately after being charged.

Summary and Conclusion

Gas Evolution

The reduction of magnetite to wustite and of wustite to iron result in the evolution of relatively large volumes of gas from the sponge iron fed into a steelmaking furnace. The volume of the gases evolved is proportional to the degree of metallisation of the DRI provided that there is sufficient quantity of carbon in the DRI to react with the oxides. The volume of the gases evolved is not appreciably influenced by the rate of heating and the size of the DRI grains used in the evolution studies. The final reduction of the DRI pellets becomes complete before they melt.

Heat Transfer and Modelling

Short-term conduction is the dominant mechanism for transfer of heat to inert pellets immersed in a hot slag that is at rest. Because of the changes of the thermal properties of the sponge iron as it is reduced, the rate of heating of a fully metallised pellet immersed in a motionless bath of slag is greater than that of a partially metallised one. Evolution of gas from the DRI pellets stirs the slag and changes the heat transfer characteristics of the bath.

The model calculations indicate that the melting rate of the pellets with vigorously boiled slags is substantially

Table 4. Specifications of DRI pellets.

Property	Pellets						
	1	2	3	4	5	6	7
Fe (%)	84.16	85.77	87.38	38.99	90.58	92.18	93.79
Oxygen (%)	6	5	4	3	2	1	0
Carbon (%)	4.25	3.54	2.83	2.12	1.42	0.71	0
Gangue (%)							
(Acid)	5.59	5.69	5.79	5.89	6.00	6.11	6.21
Density	2.77	2.72	2.68	2.63	2.59	2.54	2.50
Diameter (cm)	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Metallisation (%)	81.35	84.75	88.02	91.18	94.22	97.16	100

Table 5. Arc furnace operating data.¹²

Shell Diameter (m)	3.34
Capacity (tons)	25
Heat Time (tap to tap) (h)	1.5
Charging Period (h)	1.3
Pellet Charge (%)	100
Basicity	1
Slag Temperature (°C)	1600
Average Height of Slag (cm)	15
Slag Density (g/cm ³)	2.9

greater than for slags at rest. Pellets of smaller size melt faster. Pellets of higher density may pass through the slag and melt rapidly at the slag/metal interface if the temperature of the bath can be maintained uniform and well above the melting temperature of the DRI pellets. A minimum quantity of gangue and a slag basicity of unity are desirable.

The influence of various design variables on the melting time of the pellets can be easily verified and the maximum melting rate of the pellets can be calculated from the model. The computer model developed is well suited to predict the melting time of the DR pellets of various sources and specifications in hot metallurgical slags.

Acknowledgments

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Appendix: Heat Transfer

The transfer of heat from the liquid slag to the pellet occurs by means of conduction and free and forced convection. Since the densities of the ferrosilicate slags do not change appreciably when they solidify, the movements of the solid liquid interface do not appear to significantly affect the motion of the fluid around the pellet. A simple calculation shows that the effect of the movements of the solid/liquid interface on the thickness of the thermal boundary layer around the pellets is also not appreciable.⁵

The overall Nusselt number of the slag can be defined as follows:

$$Nu \equiv \frac{2h(R + \theta)}{\alpha \rho C_p} \quad (8)$$

where h is the coefficient of heat transfer, R is the radius of the pellet, θ is the thickness of the slag shell and α , ρ and C_p are the thermal diffusivity, the density and the specific heat of the liquid slag. The Nusselt number for a stationary sphere submerged in a motionless body of liquid can be calculated from the solution of the conduction equation

in spherical coordinates (Eq 9)⁶

$$\frac{T - T_\infty}{T_i - T_\infty} = \frac{R + \theta}{r} \operatorname{erfc} \frac{r - R - \theta}{\sqrt{\pi \alpha t}} \quad (9)$$

where T_∞ is temperature of the bulk, T is temperature at time t after immersion and at radial distance $r > R$ from centre of the sphere, and T_i temperature at the solid/liquid interface. This solution is only valid for short terms, when the velocities generated in the liquid because of development of nonuniform temperature profiles are small. The coefficient of transfer of heat determined from the above equation leads to the following correlation:

$$Nu = 2 + 2(R + \theta) \sqrt{\pi \alpha t} \quad (10)$$

If the temperature of the bath is substantially different from that of the surface of the particle, the effect of free convection should also be included in the computation of the Nusselt number. In contrast to the relatively rapid heating of the particle by conduction, the contribution of natural convection is not important during the initial transient period, when the Nusselt number for natural convection rises from zero to a maximum of about 4.⁵ The contributions of long term conduction and steady state free convection on transfer of heat to the particle are determined from the following empirical expression:⁷

$$Nu = 2 + 0.1 Gr^{1/4} \cdot Pr^{1/3} \quad (11)$$

when the quantity of the combination $Gr^{1/4} \cdot Pr^{1/3}$ is not greater than 200.

Transient forced convection may be generated when the pellet is plunged into the liquid slag. Since the actual liquid velocities produced by the plunged pellet are not defined, the available correlations cannot be conveniently utilised to predict the contribution of forced convection to heat transfer to the pellet during the initial transient period. Because of the relatively large Prandtl number of steel-making slags ($Pr \sim 100$ to 500) and from the experimental results, this period does not appear to exceed a few seconds.

The gases evolved from DRI pellets are a source of agitation in the steelmaking slags. The data of Levins and Glastonbury⁸ — as described by Eq 12 for heat transfer — are employed to determine the Nusselt number of the slag. This is calculated from the rate of dissipation of energy by ascending gas bubbles per unit mass of the slag,⁹ ϵ , based on the assumption that Kolomogoroff's theory of isotropic turbulence can be applied to steelmaking slags agitated with gas bubbles.

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

In the above equation ν is the effective kinematic viscosity of the slag.

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