CHAPTER II

LITERATURE SURVEY

Areas relevant to the heating and melting of DRI materials in steelmaking slags are catalogued in three articles:

A. Steelmaking with D-R Spong Iron as compared to other steelmaking methods such as scrap remelting or conventional blast furnace-BOF process,

B. Simulation Models used to predict the course of events during the melting of cold particles charged into a steelmaking furnace,

C. Thermal Conductivity of Slags serving as a principal medium for heating DRI materials.

A. Steelmaking with D-R Sponge Iron

In steelmaking via direct reduction, the total removal of oxygen from iron-bearing minerals is achieved during two stages:

1. primary reduction of ore into sponge iron,

2. final reduction and melting of the sponge in a steelmaking furnace.

Commercial methods developed to achieve the former stage--known as direct reduction--are described in Section 1. The nature of the direct reduced materials is discussed in Section 2. Final reduction and melting of the sponge iron products in an arc electric furnace as an alternative to conventional processes is discussed in Section 3.

1. Direct Reduction of Ore

Numerous processes for reducing the iron rich ores without a melting stage have been developed since 1950. Several of them are now in operation. There is an extensive number of papers written about development, operation, and advantages of these processes.[1-25]

Table 2-1 Principal Features of D-R Processes.[1-25]

Process	Retort	Shaft, Countercurrent		
	HYL	MIDREX	PUROFER	ARMCO
Reductant	Gas	Gas, recuperative	Gas, regenerative	gas
Product	Pellet	Pellet, Lump Ore	Briquette	Pellet, Lump Ore
Reduction Temp., °C	1000-1100	875	1000	900
% Met.	83-90	92-96	92-95	92-95
%C	1.5-2.2 (Fe_3C)	0.7-2.0 (Fe_3C)	1.4	-
Operation period, hr	12	6	-	-
Year of commercialization	1955	1969	1976	1972
Capacity in operation, 1000 ton/yr	150-600	200-600	150-350	380
Sponsor	HYL, Mexico	Midland-Ross, U.S.	Thyssen-Purofer, Germany	Armco, U.S.
Other features	4 independent reactors in series	Two unit operation 1. gas reformer 2. furnace	Hot briquetting of products	Once-through flow of reducing gas

Basic features of the best known direct reduction techniques that have practically been implemented are summarized in Tables 2-1 and 2-2.

As is illustrated in the tables, direct reduction of ore is accomplished either by a stream of reducing gas ($CO+H_2$) or by direct contact of ore with solid carbon. The specifications of the direct reduction fuels have been studied by a number of authors.[1,5,26,27] The majority of direct reduction processes involve gaseous reduction of agglomerated ore at about 1000°C or less. The ore is heated in a reduction furnace (Retort, Shaft or Fluidized Bed) and reduced with a flow of preheated reducing gas (cf. Tables 2-1 and 2-2).

In the solid reduction processes, a mixture of coal and limestone (or dolomite) is fed with iron ore into a sloping rotary kiln in which a long constant temperature zone of about 1000°C is maintained by means of a series of air injectors positioned along the kiln (Table 2-2). The addition of limestone is to scavenge the sulfur content of the coal.

2. Nature of D-R Materials

The quality of direct reduced materials has a substantial effect on both direct reduction and steelmaking processes. The criteria for desirable physical and chemical specifications of these materials for both cases are given.[26-31]

a. Physical Character

Metallized materials in the iron and steel industry are produced in four different shapes: pellets, briquettes, sinter, and lump ore.[30] These materials are produced by agglomeration and subsequent direct reduction of fine ores, flue dust, ore concentrates, ore fines, and

Table 2-2 Principal Features of D-R Processes.[1-25]

Process	Fluidized Bed		Rotary Kiln		
	FIOR	HIB	SL/RN	KRUPP	ACCAR
Reductant	Gas, recirculation	Gas	Coal	Coal	Coal, oil, gas
Product	Briquette		Pellet, Fine Ore	Pellet, Lump Ore	
Reduction Temp., °C	600	700	1000	950-1050	1000
% Met.	88-93	70-75	92-95	98	92-95
%C	$\leq$2.0	1.0	Low	-	0-1
Operation period, hr	-	-	5	-	-
Year of commercialization	1966	1973	1960	1973	1976
Capacity in operation, 1000 ton/yr	400	650	60-400	150	80-400
Sponsor	Exxon, U.S. A.G. McKee	U.S. Steel	Canada Steel	Crupp, S. Africa	Allis-Chalmers, Canada
Other features	4 pressurized reactors in series, ore fines 0.04 to 9.5 mm	Used as feed of blast furnace, ore fines	Coal volatiles combusted with air in the kiln to produce heat	countercurrent gas flow, good temp. control in kiln	Fuel flexibility

other iron-bearing particles of small size into granular, coarse particles of relatively high permeability. Depending on the type of the raw material and the direct reduction process employed, the density and the specific area of the products vary from 1.5 to 4.0 g/cm^3 and 0.5 to 4.0 m^2/g, respectively.[29]

For efficient operation of various direct reduction processes, certain physical specifications such as size, shape, density, porosity and mechanical strength must be met. Elliott[1] has described the desirable size of the ore feeds of several direct reduction techniques. George and Meadowcroft[28] have discussed the essential characteristics of SL/RN pellets utilized in Stelco blast furnaces. Their results show that the optimum pellet size for SL/RN process is 0.6~1 cm in diameter. They indicate that the degree of metallization of materials produced by the SL/RN process is independent of the particle size. For small size particles, better mixing of the charge with the solid reductant should lead to a greater production rate. However, the formation and growth of accretions on the wall of the kiln will be promoted, once the size of particles is under 0.2 cm. To scale off such accretions, the kiln should periodically be bored out. Besides, for particle sizes of less than 0.6 cm, the tendency for sulfur pickup will be enhanced.

The optimum ASTM tumbler index for proper operation of blast furnace and kiln without formation of accretions on the wall of the kiln is suggested by the above authors to be 95 percent + 0.6 cm particles after tumbling. The equivalent compression strength is given as 200 Kg/pellet for 1.3 cm pellets.

b. Chemical Character

The level to which iron oxides can be reduced by various direct reduction processes is given in Tables 2-1 and 2-2. This level is usually expressed in terms of the percentage of the total iron that may be present in reduced form and is called the degree of metallization. The chemical composition of the metallized charge affects the quality of the steel product. The levels of sulfur, phosphorus, acidic gangue, and acidic binders in the metallized iron must be low to decrease the required amount of fluxes (burnt lime) necessary for removal of these constituents from the steel by slagging.[1]

The effect of the silica content of the ore on the power consumption of the electric arc furnace is given by George, et al.[28] For a low power dissipation, they have suggested a maximum of 3.5 percent silica in the prereduced pellet.

One of the difficulties in using prereduced materials is their susceptibility to reoxidation even at atmospheric temperatures.[32,33] The heat of oxidation is usually stored in the D-R particles, due to their low thermal conductivity and accelerates the rate of reoxidation. The stability of metallized materials depends upon the nature of the direct reduction employed for their production. It is well known, for instance, that metallized materials reduced at the higher temperatures are less susceptible to reoxidation.[34,35]

To reduce the rate of reoxidation of D-R materials, they may be compacted into high density briquettes.[36,37] Besides, they must be stored under dry and, if convenient, inert atmospheres. Carburizing the surface of particles is also a way of decreasing their susceptibility to reoxidation.

3. Electric Steelmaking Practice

Three-phase direct arc furnaces have been used during the past twenty years for production of plain carbon steels by melting scrap and iron-rich ores.[38,43] In these furnaces, the arcs are struck between the charge and three vertical electrodes. The detailed description of the electric furnace operation is given by a number of authors.[30,38,39]

Electric steelmaking processes are generally divided into two categories, (a) acid practice, and (b) basic practice.

The physical and chemical character of the charge and its arrangement in the furnace can affect the melting time and the lining life of the hearth. A mixed feed of fairly uniform density, with a mixture of medium and light scrap will present an ideal charge of fairly uniform resistivity.[38,43] On top-charge furnaces, it is desirable to locate some heavy scrap low in the charge under the electrodes to prevent the bottom of the hearth from being damaged by the arcs. The total operation requires about 3 hours from tap to tap for a 100-ton capacity furnace.[43]

The most successful application of basic arc practice is the continuous feeding of DRI materials into the pool of slag and metal with or without use of scrap, while maintaining full power supply and adjusting the composition and temperature of the bath.[39-42] A combination of DRI and scrap is in many cases charged to the electric furnace.[43] Because of the lower cost of DRI, it is however desirable to use as much sponge as possible. Various methods may be used to charge metallics continuously into the furnace. Celada and Quintero[43] have described different techniques employed by HyLSA and the results obtained. They have fed DRI materials into the furnace by several methods such as: continuous loading through the wall,continuous loading through the roof using one hole directed to the center of the delta, and continuous loading through the roof using one and two holes directed between the electrodes and the wall. They have also used batch type feeding of scrap and DRI as described previously.

Much has been written about the use of DRI metallics as a principal charge to the electric arc furnace and as a way of diminishing the cost of the steel products and increasing the production rates.[43-52]

Continuous charging of direct reduced materials of low degrees of metallization presents a vigorous boil in the slag that may result in production of a foamy slag. Such a slag can shield the walls and roof of the furnace from the intense radiation of the arcs.[1,39] The evolved CO in this case decreases the density of the slag and increases its volume. The excess of slag can flow out of the furnace from the openings made for removal of the slag. The continuous utilization of the radiated heat, for melting DRI materials can furthermore reduce wear on the lining that may occur in the normal scrap melting practice.[33,38]

The results of Sibakin et al.[39] show that a reduction in refractory consumption of 27 percent can be obtained, once the sponge materials are continuously charged into the arc furnace. These results also show that using about 75 percent DRI can reduce the operation time of the arc furnace from three hours, for a total scrap load, to as little as

1.5 - 2 hours. This reduction is equivalent to an increase in production rate of up to 50 percent with a reduction in power consumption of 40 KWh/ton. This improvement is attributed to the simultaneous charging and refining operation, low content of tramp elements in the charge, and reduction in the number of recharges and the amount of heat dissipation associated with swinging aside the top of the furnace.

Post and Ameling[34] have reported several improvements in operation of Hamburger Stahlwerke's electric furnaces such as productivity increase, increase in the proportion of power-on time, decrease of electrode consumption, yield increase, and decrease in lime consumption as a result of continuous feeding of highly metallized Midrex pellets. Utilization of such materials has enabled them to produce high quality steel grades while using cheap scrap grades as a supplementary charge to the furnace. They have suggested an optimum degree of metallization of about 93 to 94 percent for minimum energy consumption and higher than 94 percent for optimum production rate.

Electric steelmaking with DRI materials has several other advantages relative to the other steelmaking processes, too. The low content of tramp elements, for example, allows the steelmaker to use DRI for producing a wide variety of steels. However, there are also a number of restrictions to the increase in DRI utilization due to the limited supplies of high quality ores that can meet the minimum standards for production of DRI materials suitable for arc furnace, and the limited availability of natural gas and electric power.[1]

Compared with traditional blast furnace-BOF practice, direct reduction-arc furnace operation requires a lower investment cost per ton

Table 2-3 Important Features of DRI-Steelmaking Practice.[5,27,45,54]

ADVANTAGE		DISADVANTAGE
Compared to BOF-Blast	**Compared to Scrap-Arc**	**Comp. to Scrap-Arc**
1. Low capital cost (32% less than Blast-BOF for 1 million ton/year capacity).	1. Possibility of continuous feeding	1. Low iron content as compared to slag.
2. Low level of air pollution.	2. Consistency of chemical analysis.	2. Low packing density.
3. Low production cost (8% less than Blast-BOF).	3. Low and known tramp elements (Cu, Sn, Ni, Pb, etc.).	3. Low quality product when high S and P ores used.
4. High flexibility in locating plants.	4. Less fluctuations in price of raw materials.	
5. Less sensitive to cost of fuel than Blast-BOF (1/4 of cost of billets as compared to 1/3).	5. Easy handling.	
	6. Less noise.	
	7. Better protection of refractory as a result of formation of frothy slag due tq the evolved bubbles.	
	8. Possibility of shortening of Arc-refining period due to the uniformity of physical and chemical properties.	
	9. Production of high quality steel.	
	10. Possibility of using various raw materials.	
	11. Lower production cost (23% less than scrap-Arc).	

of steel.[5,27,46] Nevertheless, a direct reduction steelmaking plant is well able to produce as much as half a million tons of steel per year, while a relatively large blast furnace is likely to have an annual capacity of two to four million tons of pig iron.[5] These figures indicate that a considerable potential exists for substituting direct reduction steelmaking methods for the traditional ones, especially for smaller production units.

The production and consumption of direct reduced iron has increased rapidly during the past decade. While in 1970 the capacity of direct reduction plants was slightly more than a million ton, in 1980 this amount will exceed 30 million tons.[2,5,44] Yet, greater growth in production of DRI is expected to be achieved in the foreseeable future. Such growth may diminish the enhanced demand for the world supply of scrap that may become chronic in the future.

The important features of DRI-arc steelmaking practice as compared to the other steelmaking processes are summarized in Table 2-3.

B. Heat Transfer Models

Numerical models based on heat conduction equations have been widely used to describe the temperature fields inside an object being heated, in terms of time and space.[55-60] To develop such models, the pertinent partial differential equations and their boundary conditions are translated into finite-difference equations and are solved by a high-speed computer.

An example of such models is the one developed by Elliott and Nauman.[57,58] To formulate the finite difference equations, the above authors have used the simplified form of the general heat conduction equation in spherical coordinates for one-dimensional heat flow:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial T}{\partial r}\right) = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (2.1)$$

where α, T, t, and r are thermal diffusivity, temperature, time, and distance from the origin of the coordinates, respectively. Employing the dominant boundary conditions, they have been able to solve this equation for the temperature distribution in a cold solid sphere immersed in a hot liquid environment.

As a result of the transfer of heat into the sphere, a shell of solid slag freezes on its surface, once the sphere is submerged into the bath. This shell grows to a certain thickness initially, and will remelt later. If the liquid medium has a sufficiently high temperature, the original sphere also will melt, eventually.

For the heat transfer conditions illustrated in Figure 2-1, the boundary conditions may be described with the following equations:

$$T = T_\ell \qquad r = L \qquad (2.2)$$

$$\bar{h}(T_\infty - T_\ell) = k\left(\frac{\partial T}{\partial r}\right)_L - \Delta H.\rho . \frac{\partial L}{\partial t} \qquad (2.3)$$

$$k\left(\frac{\partial T}{\partial r}\right)_{R+} = k\left(\frac{\partial T}{\partial r}\right)_{R^-} \qquad r = R \qquad (2.4)$$

$$T = T_\infty \qquad r = \infty \qquad (2.5)$$

$$\frac{\partial T}{\partial r} = 0 \qquad r = 0 \qquad (2.6)$$

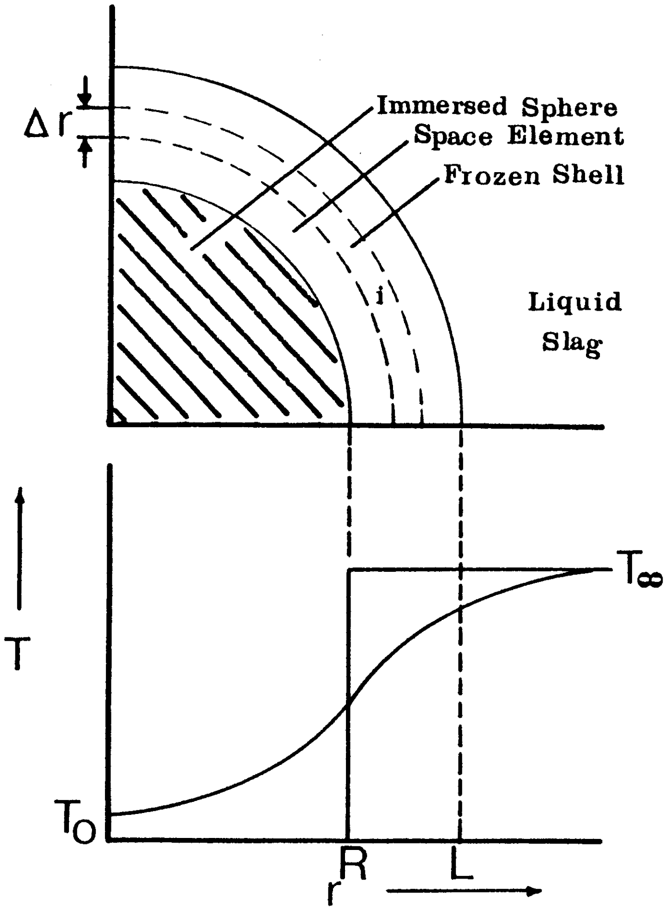

Fig. 2-1 Temperature Profile for Cold Sphere Immersed in Hot Liquid Slag.

where ρ, k, ΔH, and T_ℓ are density, thermal conductivity, heat of fusion and the liquidus temperature of the slag respectively, T_∞ is the real temperature of the bulk slag, R is the radius of the sphere, $\bar{h}$ is the average heat transfer coefficient and L is the distance from the center of the sphere to the solid-liquid interface. Initially, there is no frozen shell of slag and the temperature throughout the slag is constant, T_∞. Converting the partial derivatives to finite difference ratios, Equations (2.1) to (2.6) can be written in the form of finite-difference-equations. The new equations will yield both the future temperature of each space interval along the radius of the particle, $T_{i,j+1}$, and the position of the liquid-solid interface, L_{j+1}, at a time t after the present time j Δt:

$$T_{i,j+1} = T_{i,j} + \alpha \frac{\Delta t}{\Delta r} \cdot \frac{A_i}{V_i} (T_{i+1,i} - T_{i,j}) + \alpha \frac{\Delta t}{\Delta r} \cdot \frac{A_{i-1}}{V_i} (T_{i-1,j} - T_{i,j}) \qquad (2.7)$$

$$L_{j+1} = L_j + \frac{k}{\rho \Delta H} \cdot \frac{\Delta t}{\rho_j} (T_{i-1,j} - T_\ell) + \frac{\bar{h}}{\rho \Delta H} \Delta t (T_\infty - T_\ell) \qquad (2.8)$$

where A_i and V_i are mean surface area and mean space volume of element i. The value of ℓ_j is chosen to be less than Δr and is used to indicate the movement of the interface between space intervals:

$$L_j = i \, \Delta r + \ell_j \qquad (2.9)$$

Starting with the specified initial conditions, the above equations can be used to compute both the temperature distribution throughout the body and the position of the interface at any time by a step-by-step computation.

A study on the transient transfer of heat to cylindrical iron specimens immersed in carbon saturated liquid iron has been made by Kim and Pehlke.[67] They developed a numerical model for transfer of heat, solidification and remelting of a carbon-rich crust of iron on the surface of specimen similar to the one developed for spherical particles.[57]

Ehrich, Chuang, and Schwerdtfeger[60] have solved Equations (2.1) to (2.6) by using the method of Green's function and have calculated the melting time of a sphere of a pure metal immersed in its own melt. They have converted Fourier's second law, Equation (2.1), and the boundary conditions to integral equations and solved them by numerical technique.

George and Damle[61] have solved the same equations with the method of lines for conditions of combined heat transfer and solidification in spheres, and have tested their numerical results against known data. Grimado and Boley[62] have used the embedding technique to solve the spherical heat conduction problem, while Pedroso and Domoto[63] have obtained the perturbation solution of the problem by using a series expantion of the general solution and substituting in the equations of heat transfer. Hung and Shih[64] have similarly obtained perturbation solutions of inward and outward solidification of a saturated liquid in spherical and cylindrical containers. Their quasi-steady state approximations have been comparable to the other perturbation solutions and have been found satisfactory for practical applications. Chuang and

Ehrich[65] have solved the transient diffusion problem with moving boundary in spherical coordinates by applying the Green's function to convert the governing transfer equations to an integral form. A comparison of their approximate solutions with the computer results has proved the validity of their method. The solidification of cylinders and spheres of metals has also been studied by Kern and Wells.[66] Based on the assumption of a linear temperature profile in the solidified shell, they have developed a model that predicts the movement of the solidification front as a function of time.

Although the above procedures have been able to yield approximate analytical solutions to the heating and melting of spherical objects immersed in hot fluids for a series of specific conditions, there is not an exact solution as yet available that satisfies the conditions governing the system. Besides, the basic assumptions concerning the constant thermo-physical properties of materials that are always postulated through developing these solutions introduce a number of restrictions on the applicability of the results. Only numerical techniques seem to be capable of giving valid solutions to the heating and melting systems of the real case, at the present time.

C. Thermal Diffusivity of Slags

Thermal properties of oxide phases present as the slag in pyrometallurgical processes have an impact upon the transfer of heat to the particles immersed in the slag. Yet, very little is known about the thermal properties of these phases.

The only definitive measurements of the thermal diffusivity of synthetic steelmaking slags have been made by Fine, Enge and Elliott,[69] Foo and Elliott,[70] and Nauman, Foo and Elliott.[71] For measuring the thermal conductivity of such slags, conventional methods are not applicable due to the highly corrosive nature of these slags at the relatively high temperatures at which the tests must be made. These temperatures range from 1200 to 1600°C. Elliott[68] has described the experimental problems associated with thermal diffusivity measurements for liquid silicate slags. Fine, et al.[69] have measured the effective diffusivities of slags with basicities (lime/silica ratio) of 1.0 and 1.5, and FeO contents of up to 25 percent in the silicate. The results of their studies have been fitted to an equation relating basicity, FeO content and temperature to the apparent thermal diffusivity of the synthetic oxides:

$$\alpha_{eff} = 0.001(1.5-0.5B) + 0.018(T/1500)^3/(\%FeO)^{0.8} \ (cm^2/sec) \quad (2.10)$$

Equation (2.10) is valid for temperatures ranging from the liquids temperature of the slag to 1750°K.

The measurements of Fine, et al.[69] and Foo[70] show that the effective thermal diffusivities of glasses whose compositions are similar to metallurgical slags range from 0.002 to 0.008 cm^2/sec. The values obtained for igneous rocks[73,74] and typical coal ash slags[75] are in the same range.

Gibby and Bates[73] used a high temperature laser pulse technique to measure the thermal diffusivity of basalt. Murse and McBirney[74] measured the thermal conductivity of a synthetic lunar rock by employing a radial heat-flow technique. Both results showed that the thermal diffusivity of the rocks decreases as the temperature increases around the melting point.

Bates[75] used the high temperature laser pulse technique to measure the thermal diffusivity of several coal ash slags. Fujisaw, et al.[76] measured the thermal diffusivity of Mg_2SiO_2, $FeSiO_4$ and NaCl at high pressures and temperatures. They studied the effects of olivine-spinel phase transition on thermal diffusivity of Fe_2SiO_4.

The works of Bates[75] indicated that in addition to the composition, the microstructure of the samples of solid slags may also have a substantial effect on the thermal diffusivities of such samples.