#### CHAPTER VII

#### MELTING D-R PELLETS

The mathematical model described in Chapter V is utilized to determine the temperature distribution, the change of chemical composition, the volume of gases evolved, the movements of the solid-liquid interface and the melting time of DRI pellets heated in a hot bath of slag. The calculations are carried out on pellets of different sources and specifications. The effects of various parameters and conditions on the rate of melting of pellets are determined. The impact of a combination of these parameters on the efficiency of the steelmaking operation is given. The optimum conditions for maximum melting rate of D-R pellets are also summarized.

Since the densities of commercial pellets and steelmaking liquid slags do not differ appreciably, it may be assumed that the pellets, after being charged into the furnace, sink in the slag long enough to be melted. The effect of the immediate submersion of the pellets, when charged, on the rate of transfer of heat and melting of the pellets is small and therefore neglected (see Section VII.C). Since the probable effect of evolution of gas on removal of melted or solid portions of D-R pellets when heated in a hot bath of slag (according to a physical model similar to the one shown in Figure 6-8) is not certain, it is also neglected. Observations.made of DRI pellets heated in a levitation furnace indicate that the pellets neither break nor explode (as may appear to happen because of gas evolution) until they melt completely. If this is the case, the predictions of the model can conveniently be used to optimize arc furnace steelmaking operation as is discussed in the last portion of the chapter.

# A. Stagnant Slag

A similar procedure to that used in Chapter VI was employed to calculate the rate of heating and melting of a typical Midrex pellet (column E, Table 5-2) and a typical HYL pellet (Column D, Table 5-2) in a synthetic steelmaking slag (column C, Table 5-1) that is initially at rest. The results are illustrated in Figure 7-1. The overall Nusselt quantities of the slag was calculated from Equations (5.11) and (5.12) for short and long times after immersion, respectively. It was assumed that the effect of the motion of slag relative to the particle which may be generated as a result of the sudden drop of the pellet into the slag on the Nusselt number of the bath is negligible (cf. Section VII.C).

Because of the large quantity of heat transferred to the surface of the pellets immediately after immersion--Eq. (5.11)-- and the great difference between the temperature of the bulk and the solidus temperature of the slag, the liquid does not freeze on either of the pellets and the calculated thickness of the shell of slag remains equal to zero throughout the heating period. Since the major influence of the evolution of gas from the pellets is on the thickness of the shell of solid slag, and the Nusselt number of the bath does not appreciably change by gas evolution, as was concluded from the experimental results discussed in the previous chapter, the evolution of gas does not appear to affect the heating conditions of the system in this case. The essential influences are, however, on properties of materials, such as chemical composition and heat capacity of the pellets or thermal con-

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ductivity and effective density of the pellets and the slag. The differences in properties of DRI materials result in faster heating and shorter life-time of pellet E when both pellets E and D are heated under the same circumstances, as illustrated in Figure 7-1.

#### B. Mixed Slag

The practical steelmaking slags are mixed by rising gases which evolve from DRI materials, enter the furnace as blast or form by the refining reactions. The active mixing of the slag can increase the Nusselt number of the bath as is described in reference 58. Effects of conditions and properties of the liquid slag and D-R materials on the rate of melting of the pellets are described in the following sections.

# 1. Condition of Slag

Effects of the degree of mixing and the melting temperature of slag on the melting time of the D-R pellets are discussed in the following articles.

#### a. Degree of Mixing

The degree of agitation of the slag can be inserted into the model by quantifying the dimensionless Nusselt number of the bath. The effects of agitation of the slag on the total melting time of pellet E is illustrated in Figure 7-2. The Nusselt numbers employed for calculations are also shown as a function of the time after immersion in the same Figure.

As is seen in Figure 7-2, the long-term agitation of the slag decreases the melting time of the pellet from about 90 seconds for natural convection to about 25 seconds for a violently stirred slag.



Fig. 7-1 Temp. at Center and Melted Fraction of Pellets E and D Heated in Slag C. Slag Temp., 1600°C.



Fig. 7-2 Effect of Mixing of Slag on Melting Time of Pellet E Heated in Slag C. Broken Lines Illustrate Nusselt Number of Slag.

The melting time however does not significantly change when the slag becomes overwhelmingly violent (Nu 25). The insensitivity of the melting time to the mixing of the bath at high levels of violence is due to the excessive rise of temperature at the surface of the pellet which decreases the difference between the temperature of the bulk and that of the surface of the pellet. Under such conditions, the thermal conductivity of the pellet controls the rate of heating of the pellet and its total melting time.

# b. M.T. of Slag

The melting temperature of the slags changes with their chemical composition dramatically. For the synthetic steelmaking slag C (basicity 1) identified in Table 5-1, the solidus temperature is low enough that no solid shell may form on immersed DRI pellets of ordinary specifications when the bulk temperature is maintained at 1600°C, as was described earlier. For slags of different compositions and higher basicities, however, the solidus temperature may be greater resulting in the growth of the shell of solid slag on periphery of the pellet and a decrease in the rate of flow of heat to the surface of the pellet (Notice that the solid-liquid mushy interface is assumed to be sheared off).

The effects of the change of the melting temperature of the slag on the thickness of the frozen shell and the melting time of pellet E are demonstrated in Figure 7-3. As is seen from the figure, a rise of 200 °C in the solidus temperature of the slag increases the life-time of the pellet only for 7 seconds. The difference will be even less when the effects of gas evolution on the thickness of the shell of slag are included (Figure 7-3).



Fig. 7-3 Effect of Melting Temp. of Slag on Solidification and Melting of Slag and Pellet.



Fig. 7-4 Effect of Degree of Metallization on Melting Time of Pellet E when Heated in Slag C.

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### 2. Properties of Pellet

A moderately mixed slag (Nu=15) is employed to investigate the influence of the properties of DRI on the melting time of the pellets fed into the slag.

### a. Degree of Metallization

The effect of the degree of Metallization on the melting time of the DRI pellets is illustrated in Figure 7-4. A balanced content of carbon is assumed for the total reduction of the pellets. As is seen, the melting time of the D-R pellets decreases up to about 10 percent for each 5 percent increase in the metallization degree. The enthalpies of the reduction reactions and the change of properties of materials are responsible for this decrease.

### b. Carbon Content

The effect of the carbon content of DRI on the melting time of the pellets is demonstrated in Figure 7-5. An excessive content of carbon to that necessary for the total reduction of the pellets is considered. The oxygen conrent is however maintained the same (1.99%). As is shown, the life-time of a pellet with a greater content of carbon is longer. Since the total reduction of DRI can occur with all carbon contents that are assumed, the enthalpies absorbed by the reactions do not contribute in change of the melting time of the pellet. Hence, the melting time of the pellet is not as sensitive to the change of the percentage of carbon as to that of oxygen, as can be concluded from comparison of Figures 7-5 with 7-4.



Fig. 7-5 Effect of Carbon Content on Melting Time of Pellet E when Heated in Slag C.



Fig. 7-6

Effect of Gangue Content on Melting Time of Pellet E when Heated in Slag C.

# c. Gangue Content

The effect of the content of gangue  $(Al_2O_3, SiO_2)$  on the melting time of the pellets is illustrated in Figure 7-6. For each 1 percent increase in the content of gangue of DRI, less than 1 percent increase in the melting time of the pellet is observed.

# d. Size and Density

Since the area/volume ratio of a sphere is inversely proportional to its diameter, the rate of heating and melting of the pellets decreases as their size increases, as shown in Figure 7-7. The meltingtime however increases faster than the diameter because of the resistance to transport of heat within the pellets. Susceptibility to reoxidation and convenience in shipping, storage and handling are other criteria in determining the size of the pellets.

The melting time of large pellets decreases dramatically when their density exceeds that of liquid slag because of the tendency of such pellets to pass rapidly to the slag-metal interface were melting can be completed rapidly, as is discussed in detail in references 58 and 31. If sintering or partial fusion of the pellets results in an increase in their density, similar results are expected.<sup>58</sup> Pellets of high density are not however necessarily desirable because of the difficulties in maintaining the temperature of the metal bath well above the melting point of D-R pellets, especially when a large quantity of cold DRI descends to the slag-metal interface immediately after submersion.<sup>31</sup>



Fig. 7-7 Effect of Size on Melting Time of Pellet E Heated in Slag C.



Fig. 7-8 Effect of Sudden Submersion on Center Temp. and Melted Fraction of Pellets E and D Heated in Slag C.

# C. Sudden Submersion

The effect of the sudden submersion on the heating rate of the pellets is investigated by employing the same Nusselt number as was used to identify the plunging effect during the experimental studies described in Section VI.B.3. The plunging effect was assumed to last for 2 seconds during which the contribution of the transient forced convention on the Nusselt number drops from 70 to 0. As is seen from Figure 7-8, although the temperature at the center of the pellets slightly increases, when a greater initial Nusselt number is utilized, the melting time of the pellets does not necessarily decrease. A small increase in the melting time of pellet D, for instance, is observed in Figure 7-8 when the effect of the sudden submersion is included.

The relatively large initial Nusselt number causes a rapid rise of the temperature at the surface of the immersed pellet which lowers the difference between the temperature of the bulk and that of the surface of the pellet. Since the thermal conductivity of pellet D is less than that of pellet E, this difference is greater for pellet D. The small temperature difference may result in a small rate of transfer of heat to the particle when effects of sudden immersion is eliminated, and may increase the life-time of the immersed pellet, as happens for pellet D.

# D. Melting Efficiency

The rate of production of steel from DRI in a steelmaking furnace is controlled by the rate of feeding and the iron content of D-R materials. The rate of feeding cannot exceed the rate of melting of the charge and is controlled by the melting time of the DRI pellets. Assuming an ideal

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case with uniform distribution of the pellets in the slag (so that the interaction between the pellets can be neglected and the pellets do not make cold islands in the bath) the maximum rate of feeding of the D-R pellets, F, will be proportional to the rate of melting of the pellets provided that the arcs can produce enough heat that the bulk slag does not cool off.

$$\dot{F} = C/t_{m}$$
(7.1)

In the above equation, C is a proportionality constant and is determined from the specifications of the furnace and  $t_m$  is the life-time of the pellets fed into the slag.

The iron content of DRI is related to the degree of metallization, percent carbon and the content of gangue of the pellets. Assuming 6 percent gangue and a sufficient content of carbon to reduce all of oxygen and add 1 percent carbon to the iron that can be produced from reduction of DRI, the quantity of iron produced per unit weight of D-R materials can be calculated as follows:

$$M = 0.93 - \frac{100 - \%Met}{269.8 - 1.07\%Met}$$
(7.2)

Combining Equations (7.1) and (7.2) results in the rate of production of iron from DRI.

$$p = C(0.93 - \frac{100 - \% Met}{269.8 - 1.07\% Met}) / t_m$$
(7.3)

The effect of the degree of metallization on the rate of production of iron from typical Midrex pellets is demonstrated in Figure 7-9. The melting times of the pellets are determined from the model calculations

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Fig. 7-9 Effects of Degree of Metallization and Size of D-R Pellets on Rate of Production of Iron.

(Figure 7-4). The quantity C is arbitrarily chosen for a medium size electric furnace.

Effects of the other specifications of the D-R pellets on the rate of production of iron can also be included. As is seen from Figures 7-5 and 7-6, the melting time of the pellets does not change appreciably with carbon and gangue contents of DRI. The effect of the pellet size on the rate of production of iron from DRI is calculated from the information given in Figure 7-7 based on the assumption that C is the same for all sizes employed, as illustrated in Figure 7-9.

#### E. Optimal Conditions

From discussions in this chapter, the following conclusions may be derived:

1. The life-times of the immersed D-R pellets are substantially less for mildly stirred slags than for slags at rest. Violently stirred slags are not necessarily desirable because of the relatively small change they create in the melting time of the pellets and the difficulties they may produce in proper operation of the bath (e.g. slag over-flow as a result of evolution of large volumes of gas).

2. Small changes of the chemical composition of the steel making slags do not influence the melting time of DRI pellets substantially.

3. Highly metallized pellets melt appreciably faster than less metallized pellets.

4. The influence of the carbon and gangue contents of DRI on the life-time of pellets is relatively small.

5. The pellets of smaller size melt much faster.