REDUCTION BEHAVIOUR IN FASTMET™ PELLETS

Fastmet™, a process developed by the Midrex Corporation, produces iron for steelmaking by heating pellets composed of iron oxide and coal. Here we develop several simple models of the reduction process and confirm claims made by the manufacturer about the conversion time. These models can also be used to investigate the dependence of the conversion time on controlling parameters.

1. Introduction

The iron and steel industry has a very long history dating back nearly 3000 years. Up to about the 14th century, iron was produced primarily in small stone-based furnaces with the earliest blast furnaces dating from the 15th century. Steelmaking, as we know it today, dates from the 18th century and a "steel industry" from the Industrial Revolution, with open hearth furnaces and the Bessemer Converter playing vital roles in its expansion. Today the steel industry is based mainly on the use of either advanced blast furnace technology or electric furnaces. In 1993, the global production of steel was over 700 million tonnes with the industry employing about 1 million people worldwide. All developed and most developing countries have a steel industry and while the European and Japanese industries are static or in decline and the US industry is experiencing very slow growth, the industries in parts of Asia and Latin America, for example, are enjoying medium to strong growth.

There are two approaches to modern steelmaking, one involving an integrated plant approach and the other based on electric steelmaking using mini mills. The modern integrated plant takes iron oxide as its basic raw material and using a blast furnace and a basic oxygen furnace produces steel which is subsequently cast into blooms via a continuous caster. The feed material for the blast furnace must be processed using both a sinter plant and coke ovens. Electric steelmaking, on the other hand, generally uses scrap material as its input and produces steel using electric arc and ladle furnaces.

Currently there are various pressures on large integrated steelworks. These include environmental concerns mainly associated with dust pollution and gaseous emissions of oxides of nitrogen and sulphur. The capital cost of replacement of an ageing plant can now exceed $2 billion. There are also increasing quantities of low grade scrap suitable for feed material for electric steelmaking. The trend worldwide, therefore, has been towards electric steelmaking and the traditional integrated plant route for steelmaking has lost market share.

There has been strong growth in the electric steelmaking sector of the steel industry recently. As mentioned above, one factor has been a sufficient supply of low grade scrap. However, there has been an increase in residual contaminants in low grade scrap and high grade scrap is becoming more difficult to obtain in sufficient quantities. This has led to extensive investigations of alternative feedstock for electric steelmaking furnaces and direct reduced iron has proved an excellent scrap substitute.

All direct reduction iron has the common feature that the oxygen associated with the feed material is removed at temperatures which are below the melting point of any of the materials involved. The process requires high iron content raw materials with low gangue (nonferrous minerals and other impurities). The final product is usually in briquette or pellet form and most direct reduced iron is produced for "in house" use although there is a limited but increasing merchant trade.

The foremost methods for making direct reduced iron are gas–based or coal–based, with gas–based processes accounting for more than 90% of the world wide production.
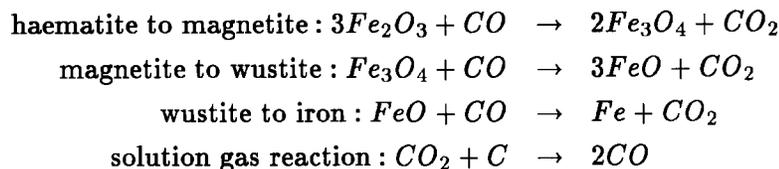
A typical gas–based process requires large quantities of cheap natural gas and uses gas combustion both to heat the feed pellets and to reduce the raw material to iron. The pellets are usually 9–16 mm in diameter and are heated to between 800 and 840°C with the material having a residence time of 5–6 hours.

Fastmet^{TM} is a coal-based direct reduced iron process developed by Midrex Direct Reduction Corporation in the U.S.A. Finely ground coal, iron ore and a small amount of binder are mixed together and formed into pellets and dried to remove moisture. These pellets are then fed into a rotary hearth furnace in a layer one to two pellets deep. As the hearth rotates the pellets are heated to 1250–1350 °C using gas, oil or coal-fired burners. Lepinski, from Midrex, states (Lepinski, 1993) that a typical residence time is 6–12 minutes, depending on the feed material, after which between 90 and 95% of the iron oxide is converted to metallic iron. This compares with residence times of several hours for other direct reduction processes.

The MISG addressed the question of the validation of the claims by the Midrex Corporation about the timescales for the iron reduction for the Fastmet^{TM} Process.

2. Mathematical modelling issues

The main reactions for the coal–based reduction of haematite can be summarised by the scheme:

$$\text{haematite to magnetite}: 3Fe_2O_3 + CO \quad \rightarrow \quad 2Fe_3O_4 + CO_2$$
$$\text{magnetite to wustite}: Fe_3O_4 + CO \quad \rightarrow \quad 3FeO + CO_2$$
$$\text{wustite to iron}: FeO + CO \quad \rightarrow \quad Fe + CO_2$$
$$\text{solution gas reaction}: CO_2 + C \quad \rightarrow \quad 2CO$$

Wustite is actually a non-stoichmetric compound of average formula $Fe_{0.95}O$. For convenience only the formula FeO has been used throughout this report.

From a study of the reactions associated with this process it was noted that the first two reactions proceed rapidly compared with the last two and so it was proposed to lump the last two reactions into one to give the rate controlling reaction

$$FeO + C \rightarrow Fe + CO \quad \text{(slow and highly endothermic)} \tag{1}$$
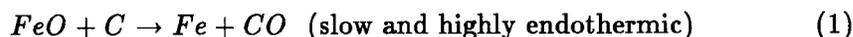
with the heat of reaction suitably modified. The heat of reaction associated with the endothermic "lumped" reaction (1) is derived from experimental values given in Walker (1986) and leads to the estimate of a requirement of 1650 kJ/kg of mixture, which we denote by R.

The participants at the MISG examined the geometry of the rotating hearth and adopted two distinct approaches to the modelling heating of the layers of the green pellets. One regards the raw material as a porous layer while the other treats the pellets individually.

Another issue of importance to the modelling is the choice of physical constants. Since the type of model to be discussed depends on the choice of these, considerable effort was expended on their estimation.

An estimate of the pellet porosity of the raw material is given by Huang and Lu (1993) as 35% and for the porosity of a packed bed a value of 50% is used. We will give the reasoning behind the estimates of the other parameters for the pellet model. The estimates for the layer model can be derived using the layer porosity. The unfired mixture is about 40% coal and 60% haematite. Since the conversion from the haematite to wustite is fast in comparison with the reaction (1) we assume for the models that the raw material is coal and wustite in the above ratios. Using the standard values (Akiyama *et al.*, 1992; Lide, 1992; Touloukian, 1970: Usui *et al.*, 1986; Usui *et al.*, 1991) with the above pellet porosity we obtained the following estimates for unfired pellets:

$$\text{Density, } \rho = 2600 \text{ kg/m}^3$$
$$\text{Specific Heat, } c = 500 \text{ J/kgK}$$
$$\text{Thermal Conductivity, } k = 0.4 \text{ W/mK}$$

and for fired pellets:

$$\text{Density, } \rho = 5100 \text{ kg/m}^3$$
$$\text{Specific Heat, } c = 300 \text{ J/kgK}$$
$$\text{Thermal Conductivity, } k = 20 \text{ W/mK}$$

When values are required for the layer geometry the values need to be recalculated using a porosity of 0.5.

The temperature of the flame, T_f, is taken to be 1800 K, though the flames can radiate at an effective rate of between 1500 K and 2100 K. The initial temperature of the pellets, T_i, is approximated at 400 K as the pellets have not cooled completely before being fed into the furnace. The temperature of the base, T_a, is taken to be 500 K for the same reason that it has not cooled to room temperature before the fresh pellets enter the furnace. The reaction temperature, T_R, is taken as 1000 K.

3. Timescales

In order to devise an approximate model for the Fastmet$^{\text{TM}}$ process, we need to estimate a time scale for each step in the process. This reductionist approach allows us to isolate the rate limiting step(s), which can then be modelled.

In the Fastmet$^{\text{TM}}$ process, the steps are

(i) heat transfer from flame to reactant bed,

(ii) heat transport through reactant bed,

(iii) absorption of heat for endothermic reaction to occur.

For each of these we now estimate a characteristic time. First, however, we must find the total energy requirements to heat the reactants from ambient and totally convert them to iron. This is given by the sum of the 'sensible' and 'latent' heats:
$$\Delta E = \rho V c \Delta T + \rho V R,$$
where ρ is the density of the reactant bed, V is the volume of the reactant bed, c is the specific heat of the reactant bed, ΔT is the temperature increase from initial to reaction temperature, and R is the heat of the reaction (endothermic).

Using the standard values decided upon at the MISG, this gives

$$\Delta E = A(5,850,000 + 64,350,000)J,$$

A being the area of the bed involved.

Now, we can begin the estimates of timescales, starting with the rate at which radiant heat is transferred from the flame to the reactant bed. It is given by

$$\dot{q} = \epsilon\sigma(T_f^4 - T_i^4),$$

where $\dot{q}$ is the energy per unit time per unit area, $\epsilon = 0.6$ is the emmisivity/absorptivity of the reactant bed (assumed as a grey body), σ is the Stefan-Boltzmann constant, T_f is the flame temperature, and T_i is the initial temperature of the reactant bed. We estimate

$$\dot{q} = 356,257Js^{-1}m^{-2},$$

which, combined with our ΔE estimate, gives the timescales for sufficient radiant heat to be transferred for the heating and conversion:

$$\tau_h = 16s$$

for the heating, and

$$\tau_c = 180s$$

for the conversion to iron.

It remains for us to estimate the rate at which heat is transported through the reactant bed. Assuming this to be primarily a heat diffusion problem, the characteristic timescale is obtained by dimensional analysis of the heat diffusion equation

$$\frac{\partial T}{\partial t} = \alpha\frac{\partial^2 T}{\partial x^2},$$

to be

$$\tau_d = \frac{L^2}{\alpha},$$

where L is a characteristic length (e.g. bed depth), and α is the thermal diffusivity. We find

$$\tau_d = 1462s.$$

This value is derived using the green pellet parameter values. As the pellet is converted, the diffusivity of the material increases dramatically and a typical time for conduction is about 34 seconds in converted material, suggesting that the Fastmet^{TM} process is limited primarily by the time required for sufficient heat to be transported through the bed (not from the flame to the bed) and by the time required for sufficient heat to be accumulated to cause the endothermic reaction.

4. Stefan model

The classical Stefan model (Hill and DeWynne, 1987) consists of heat diffusion through the converted portion of the material, driving a phase change which has an associated latent heat. The simplest case has a prescribed temperature at one end of a semi-infinite layer, and one seeks to know the position (as a function of time) of the boundary separating the phases.

The governing diffusion equation is

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}, \quad t > 0, x > 0,$$

with boundary condition

$$T(0, t) = T_f, \quad t > 0,$$

and initial condition

$$T(x, 0) = T_R, \quad x \geq 0.$$

Additionally there is the Stefan condition for the motion of the interface:

$$\rho R \frac{da}{dt} = -k \frac{\partial T}{\partial x},$$

evaluated at $x = a(t)$. Here ρ is the density of the converted material, c is the specific heat of the converted material, k is the conductivity of the converted material, R is the latent heat associated with the phase change, and $a(t)$ is the position of the interface separating the phases.

A solution is most easily found by similarity reduction (Hill and DeWynne, 1987) to be

$$a(t) = \sqrt{(2\gamma \alpha t)};$$

where $\alpha = \dfrac{k}{\rho c}$ is the thermal diffusivity of the converted material, and γ is a non-dimensional number found by solving a non-linear algebraic equation dependent upon the ratio of latent to sensible heat:

$$\beta = \frac{R}{c(T_f - T_R)} = 13.75.$$

The equation for γ is

$$\beta \exp(\gamma/2) \sqrt{(\pi \gamma/2)} \mathrm{erf}(\sqrt{(\gamma/2)}) = 1.$$

For large β, an approximate formula for γ is

$$\frac{1}{\gamma} = \beta + \frac{1}{3},$$

which accurately gives $\gamma = 0.071$ in our case.

Thus, using $\alpha = 2.614 \times 10^{-5} m^2 s^{-1}$, the position of the reaction front is given (in millimetres) by

$$a(t) = \sqrt{(3.712t)}.$$

In particular, for the reaction front to travel the full $30mm$ through the bed would take $242s$ or about 4 minutes. This will be seen to be in excellent agreement with the more complex model solved numerically in the next section.

5. Layer model

This model considers the pellets to form a one-dimensional layer of material of height L. This layer is heated from above by radiation from a gas burner of temperature T_f. The layer is resting on a solid boundary which is slowly heated by conduction from the pellets. This is schematically indicated in Figure 1 where the pellets are shown on the supporting lower boundary.
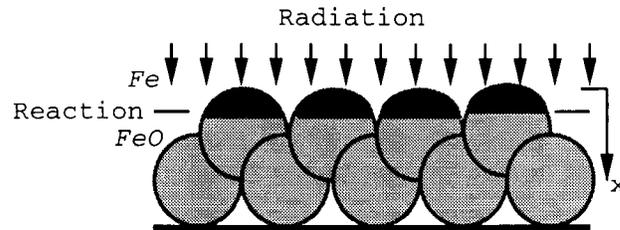
Figure 1: Schematic diagram of one dimensional heating of a layer of pellets.

It has been established that the rate limiting step in the process is the transferral of heat through the layer and not the transport of reactants. The important rate limiting step in the reduction process was established to be the endothermic reaction (1) as described earlier. The equilibrium point of this reaction is temperature dependent and is assumed to occur in negligible time. Hence the proportion of FeO, $m \in (0, 1)$, at a given temperature can be modeled by an equation of the form:
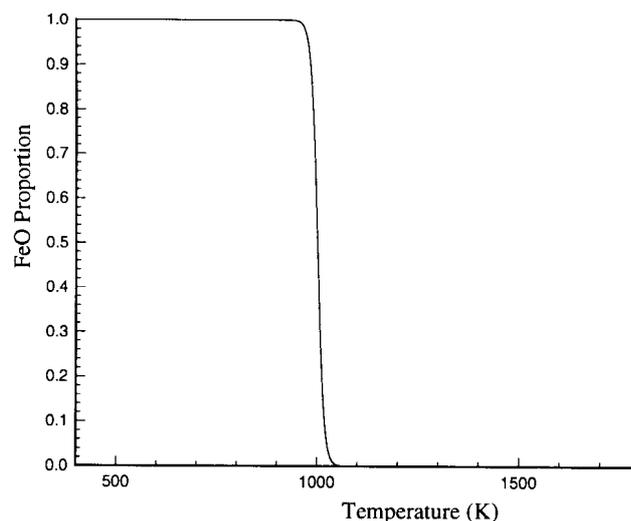
$$m = 1 - \frac{1}{1 + \exp(-3f(T - T_R))}.$$

Figure 2: Concentration of FeO at a given temperature with $f = 1/25$.

which is illustrated in Figure 2. The factor f can be adjusted to give the required range of temperature in which the reaction occurs and we take $T_R = 1000K$.

The reduction of FeO can then be modelled by a nonlinear diffusion equation for temperature with an associated sink term corresponding to the loss of heat to fuel the reaction (1):

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left\{ k(m) \frac{\partial T}{\partial x} \right\} - R\rho \frac{\partial m}{\partial t}, \qquad (2)$$

where T is the temperature, c the specific heat, ρ the density, $k(m)$ the conductivity, R the heat of reaction, and $m(x, T)$ the proportion of FeO. The conductivity is a function of m since Fe has higher conductivity than FeO. Coupled with this is the increase in porosity after the reduction. The conductivity thus has the form:

$$k(m) = 0.2 + p(1 - m) \qquad (3)$$

where p is a constant. Typically we chose $p = 9.8$ as we estimated the conductivity in the porous Fe to be fifty times the conductivity in porous FeO. This gives a typical conductivity profile as in Figure 3. In equation (2) the last term is appropriately rewritten with:

$$\frac{\partial m}{\partial t} = \frac{\partial m}{\partial T} \frac{\partial T}{\partial t}.$$

The boundary condition on the top surface, $x = 0$, due to radiation from the flame was:

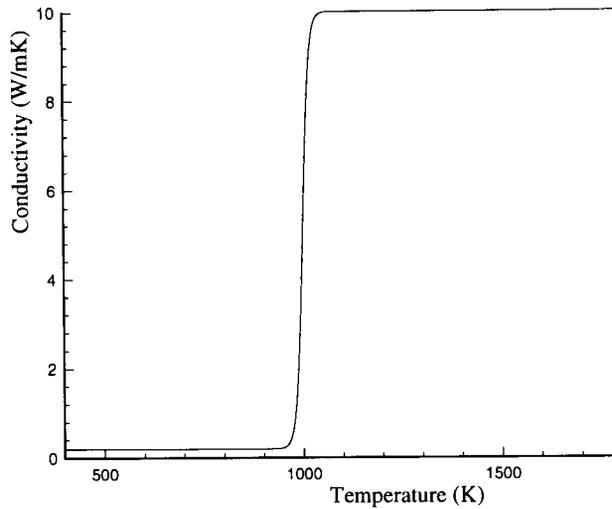$$k \frac{\partial T}{\partial x} = -\epsilon \sigma (T_f^4 - T_s^4)$$

Figure 3: Conductivity, $k(T)$, as a function of temperature.

where ϵ is the emissivity/absorptivity of the reacted bed and σ is the Stefan-Boltzmann constant. The boundary condition on $x = L$ was chosen to be:

$$k\frac{\partial T}{\partial x} = h(T_a - T),$$

where T_a is the ambient temperature of the underlying hearth, and h is the heat transfer coefficient, estimated to be 70 W/m^{2}K.

This equation was then solved numerically using a standard method of lines routine. The results for the standard parameter values are detailed below. In Figure 4 the temperature profiles for the layer are given at different times as a function of x. Note that there is a distinct inflection point where the temperature changes from a domain governed by the conductivity of Fe to a domain governed by FeO conductivity. The temperature profile is also linear in the Fe domain due to the high conductivity. This linear region is hence quasi-steady state — that is the profile could be approximated by the solution to a steady state diffusion equation and updated with time as the front of reaction moves forward.

In Figure 5 we plot the position of the reaction front as a function of time. This position was defined as the x value when the temperature was 1000 K. The time for the entire layer to be reduced is thus defined by the time when the temperature at $x = L$ is 1000 K. This reduction time is thus governed by the slope of the curve in Figure 5, called the reaction slope.

Numerical solutions were also obtained for a variety of parameter values. We found that varying either the initial condition or the boundary condition at
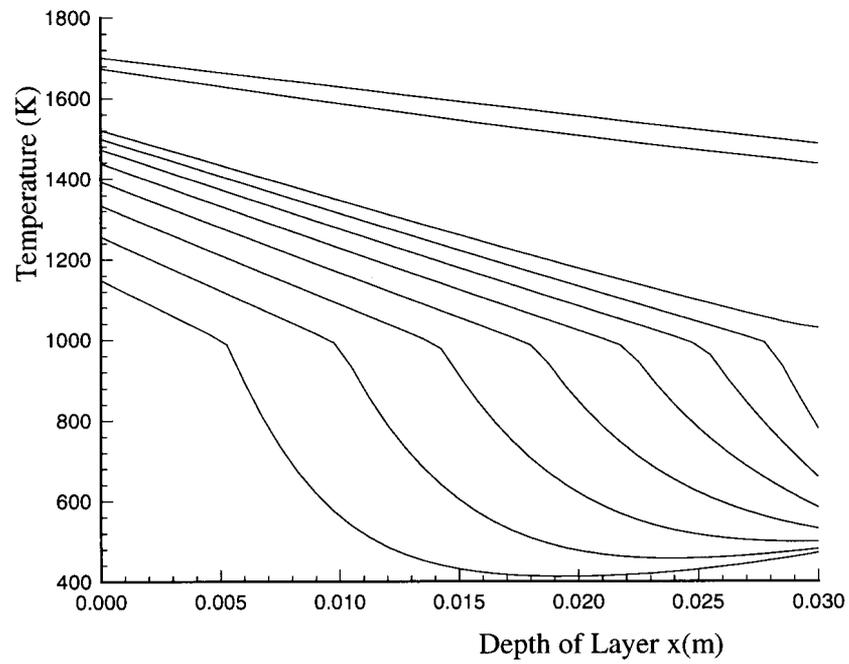
Figure 4: Temperature profiles as a function of x for 10 different times $t \in (0, 400)s$.
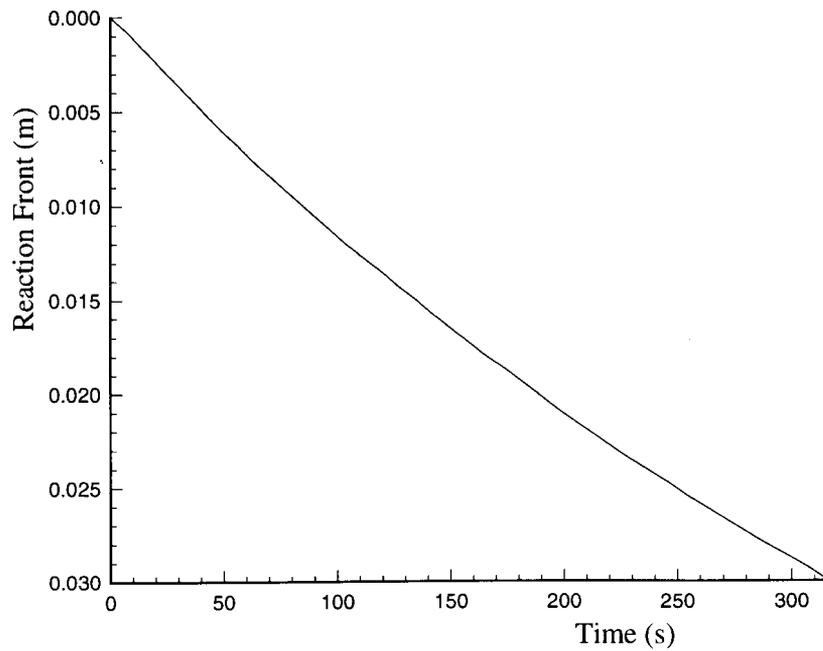

Figure 5: Position of the reaction front as a function of time.

$x = L$ had little or no effect on the reduction slope except in the last few seconds of the reaction process. The temperature profiles were in some cases altered in the *FeO* region but this had little effect on the overall reduction. Similarly the conductivity in the *FeO* region had little or no effect on the reaction slope. Varying the function $m(T)$, the equilibrium range of the reaction (1), broadened or narrowed the 'reaction front' but had little or no effect on the reduction slope and hence the time for total reduction in the layer.

We found that the process of reduction was almost entirely dominated by the heat transfer in the *Fe* region. If the conductivity in this region was increased so the slope increased. It is also apparent that, even given the crude estimates for the parameters, the time scale for this process is of the order of 300–400 seconds or 5–7 minutes.

6. Pellet model

There are certain aspects of the Fastmet^{TM} process that cannot be effectively examined using simple averaged one-dimensional models. For a start the thermal mass will vary with depth, producing a non-uniform cooking rate. Also the top layer of particles will shield the lower layer from the radiative input from the flames; so that effectively the particle layers will be radiated layer by layer. Such aspects may be of practical importance. Of course, if the variability of particle size is relatively great, if there are several layers, or if purely global aspects of the process are of interest, then such effects would average out or be of little interest. For the one or two layers envisaged here this is doubtful. Also the melting of pellets is of special concern to the manufacturers because melted particles may adhere to the rotating table. Obtaining practically useful (quantitative) information about these effects is by no means a small task, and theoretical and empirical results will need to be combined to produce the required estimates. We examined simple models here in order to display important features and to indicate how to proceed further.

As before we assume:

- The reaction time scales are all sufficiently short compared with the diffusion time scales that the reactions can be thought of as occurring instantaneously.

- The individual reactions whose overall effect is to reduce the iron ore need not be treated separately. Providing the availability of reacting agents is adequate, it's the slowest chemical process that will determine the reduction time, and also the net energy requirement is appropriate for heat

balance calculations across the reaction zone, so in context these approximations make sense. (The availability of reducing gas CO does not restrict the process.) We will in fact also avoid dealing in detail with the complex heat exchange effects that are occurring within the particles; absorbing such effects into the reaction heat term.

We develop a simple model to get a grip on the processes involved and the simplest non-trivial model involves the symmetric radiation of a particle. We thus consider a particle of radius b uniformly radiated with heat at a rate $\dot{q}$ per unit area, see Figure 6. Our objective is to determine how the radiative input and particle size influence the roasting time.
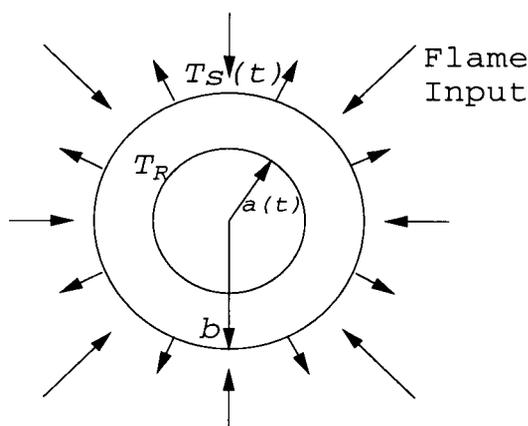

Figure 6: A symmetrically radiated particle.

The appropriate variables to describe the status of the particle at time t after the initiation of radiative input are the radius $a(t)$ of the reaction front, and the surface temperature $T_s(t)$ of the particle.

If T_R is the reaction temperature, then $\nabla^2 T(r) = 0$ governs the quasi-steady state temperature distribution in regions adjacent to the front, so that the profile through the particle is given by:

$$T(r,t) = \begin{cases} \dfrac{a(t)T_R}{r} + \dfrac{[bT_s(t) - a(t)T_R][r - a(t)]}{r[b - a(t)]} & \text{for } r > a(t) \\ T_R & \text{for } r < a(t) \end{cases}$$

Figure 7 shows a typical temperature profile. Clearly the temperature in the core will not be at the reaction temperature in the early stages of roasting, but this will not greatly alter results of interest to us.

In order to ensure that the surface receives heat at the required rate $\dot{q} = \epsilon\sigma T_f^4$ (where T_f is the effective flame temperature), and re-radiates heat at the rate
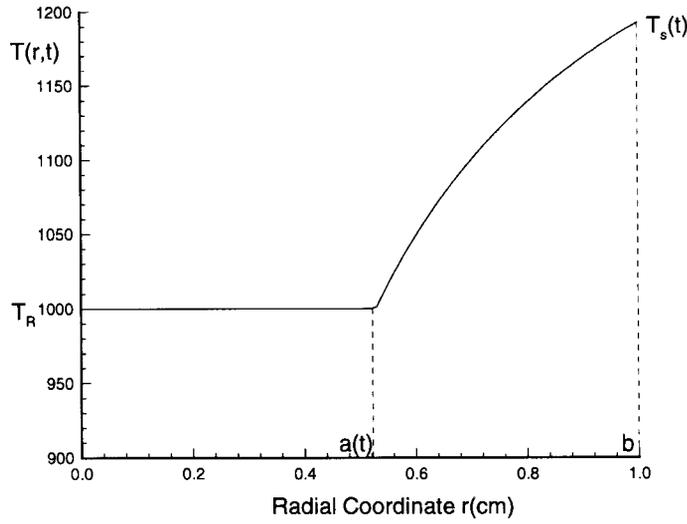
Figure 7: Temperature profile at time t.

$\epsilon \sigma T_s^4(t)$ we require:

$$k \frac{\partial T}{\partial r}(b, t) = \epsilon \sigma [T_f^4 - T_s^4(t)]. \tag{4}$$

The net heat conducted into the front per unit time must be sufficient to produce the observed iron production rate which requires:

$$-k \frac{\partial T}{\partial r}(a(t), t) = R \rho \dot{a}(t), \tag{5}$$

where R is the heat of reaction. These two conditions (4,5) are sufficient to determine equations for the two unknowns $a(t), T_s(t)$.

It is convenient to scale the equations thus:

$$r = br', \ t = t_0 t', \ T = T_i + (T_f - T_i)T'(r', t'),$$

where T_i is the initial particle temperature and where the time scale

$$t_0 = \frac{R \rho b}{\epsilon \sigma T_f^4} \equiv \frac{R \rho b^2}{k(T_f - T_i)\gamma},$$

is chosen to reflect our belief that the roasting time depends mainly on the ratio of the required heat to reduce the pellet to the external supply rate. In scaled terms the reaction front temperature T_R' is given by

$$T_R' = \frac{T_R - T_i}{T_f - T_i}.$$

The boundary conditions reduce to

$$\frac{\partial T'}{\partial r'}(1, t') = \gamma[1 - \{\nu + (1 - \nu)T_s'\}^4],$$

$$-\frac{\partial T'}{\partial r'}(a'(t'), t') = \gamma \dot{a}'(t'),$$

where the dimensionless groups

$$\gamma = \frac{b\epsilon\sigma T_f^4}{k(T_f - T_i)}, \quad \nu = \frac{T_i}{T_f}, \text{ and } T_R',$$

specify the important parameter combinations for the problem. The scaled temperature profile is given by

$$T'(r', t') = \begin{cases} \dfrac{a'(t')T_R'}{r'} + \dfrac{[T_s'(t') - a'(t')T_R][r' - a'(t')]}{r'[1 - a'(t')]} & \text{for } r' > a'(t') \\ T_R' & \text{for } r' < a' \end{cases}$$

A direct substitution of this form into the boundary condition requirements leads to the following equations for $T_s'(t'), a'(t')$:

$$\{\frac{a'(t')}{(1 - a'(t'))}\}[T_s' - T_R'] = \gamma[1 - \{\nu + (1 - \nu)T_s'\}^4]. \tag{6}$$

$$a'^2 \dot{a}' = -\frac{1}{\gamma}\{\frac{a'(t')}{(1 - a'(t'))}\}[T_s' - T_R']$$

$$\equiv -[1 - \{\nu + (1 - \nu)T_s'\}^4],$$

These need to be solved subject to the conditions that initially the particle surface is at the reaction temperature and the reaction surface is located at the surface, so that

$$T_s'(0) = T_R', \quad a'(0) = 1.$$

6.1 Parameter values

The pellets are of average diameter 20 mm so $b = 0.01$m. The flame temperature used previously for the layer models was 1800 K, corresponding to a radiative input of 371 kJ/m²s. Since half the particle surface is in the shadow of the radiation, the particles are radiated at an average rate of $\frac{\pi}{8}$ times the above value. Hence we shall take $\dot{q} = 140$ kJ/m²s, which corresponds to an effective T_f of 1400 K. The quoted value for $T_R = 1000K$, so the effective radiation temperature is certainly adequate to raise the temperature to that required for the reduction to take place. The dimensionless groups of practical interest are thus

$$\nu = \frac{400}{1400} \approx 0.3$$

$$T'_R = (1000 - 400)/(1400 - 400) = 0.6$$

$$\gamma = \frac{0.01 \cdot 0.6 \cdot 5.67 \times 10^{-8} \cdot 1400^4}{20(1400 - 400)} \approx 0.1$$

Both ν and T'_R vary little over the range of conditions of interest but γ can vary by a factor of 2 or 3 depending on the effective flame temperature used.

Thus the time scale is given by:

$$t_0 = \frac{1650 \times 10^3 \cdot 2600 \cdot 10^{-2}}{0.6 \cdot 5.67 \times 10^{-8} \cdot 1400^4} = 328s$$

The scaling suggests that the roasting time is of order 5–6 minutes, and, to first order, increases in direct proportion to the radius and varies inversely to the radiative heat supply rate. The smallness of γ indicates that radiative heat transfer is relatively slow compared with (metal) conductive processes over the temperature and length scales of interest.

6.2 No re-radiation case

In the absence of re-radiation the describing equations can be explicitly integrated to give

$$a' = (1 - 3t')^{\frac{1}{3}},$$

which gives an under-estimate for the reduction time of $t_0/3$ s or about 2 minutes, and provides us with a baseline for discussing re-radiation effects. Notice, see Figure (8), that the radius of the reaction zone initially shrinks slowly and then changes very rapidly as $a \to 0$. Since effectively the radiative heat is being applied directly to the reaction front in our simple model, this result (and indeed the explicit solution) might have been anticipated using elementary physical arguments. Also since the heat supplied is applied to a shrinking (and eventually vanishing) surface area, the surface temperature T_s becomes singular as $a \to 0$. Re-radiation from the particle surface will, of course, influence the amount of heat reaching the reaction zone and so will increase the cooking time in a way that is not so obvious.

6.3 Re-radiation effects

The algebraic Equation (6) can be solved for $a'(T'_s)$ and this used to eliminate a' in favour of T'_s and the result integrated directly; $a'(t')$ can then be recovered using (6). The effects of parameter variations over the ranges of interest are briefly explored and the results are displayed in Figure 9. For our purposes the parameters (T'_R, γ, ν) are treated as being independent. In practice T_f is the physical variable that can be adjusted and a variation of T_f will affect all three of the above parameters.
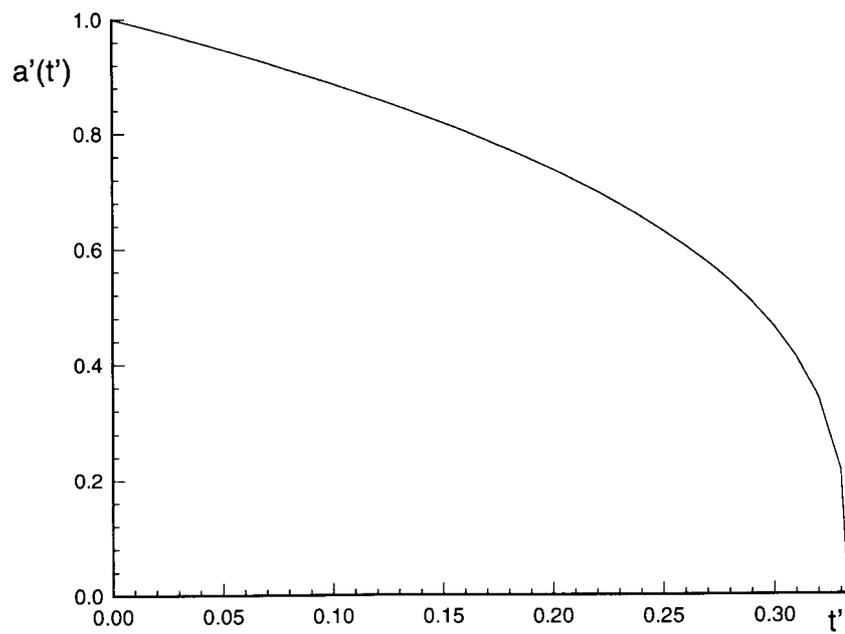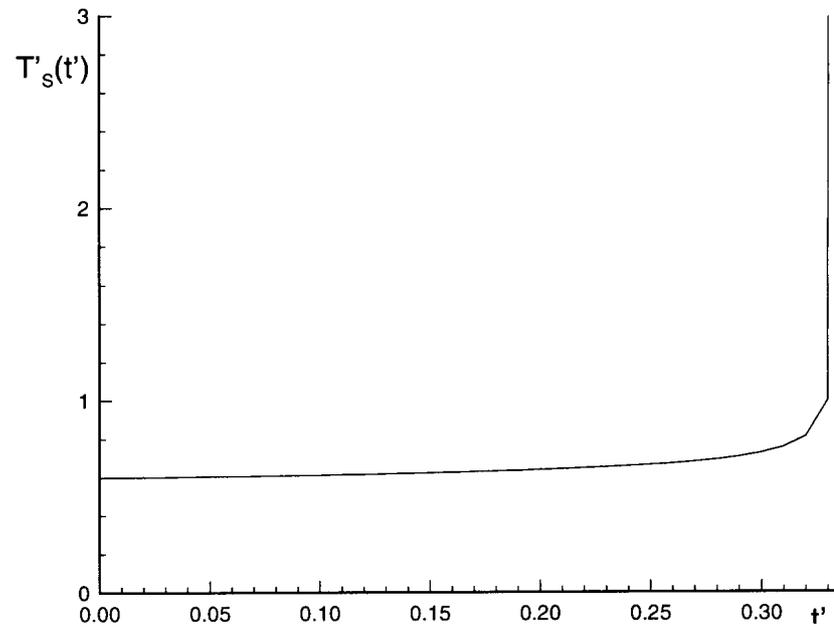
Figure 8: Solution behaviour in the absence of re-radiation, $T'_R = 0.6$.
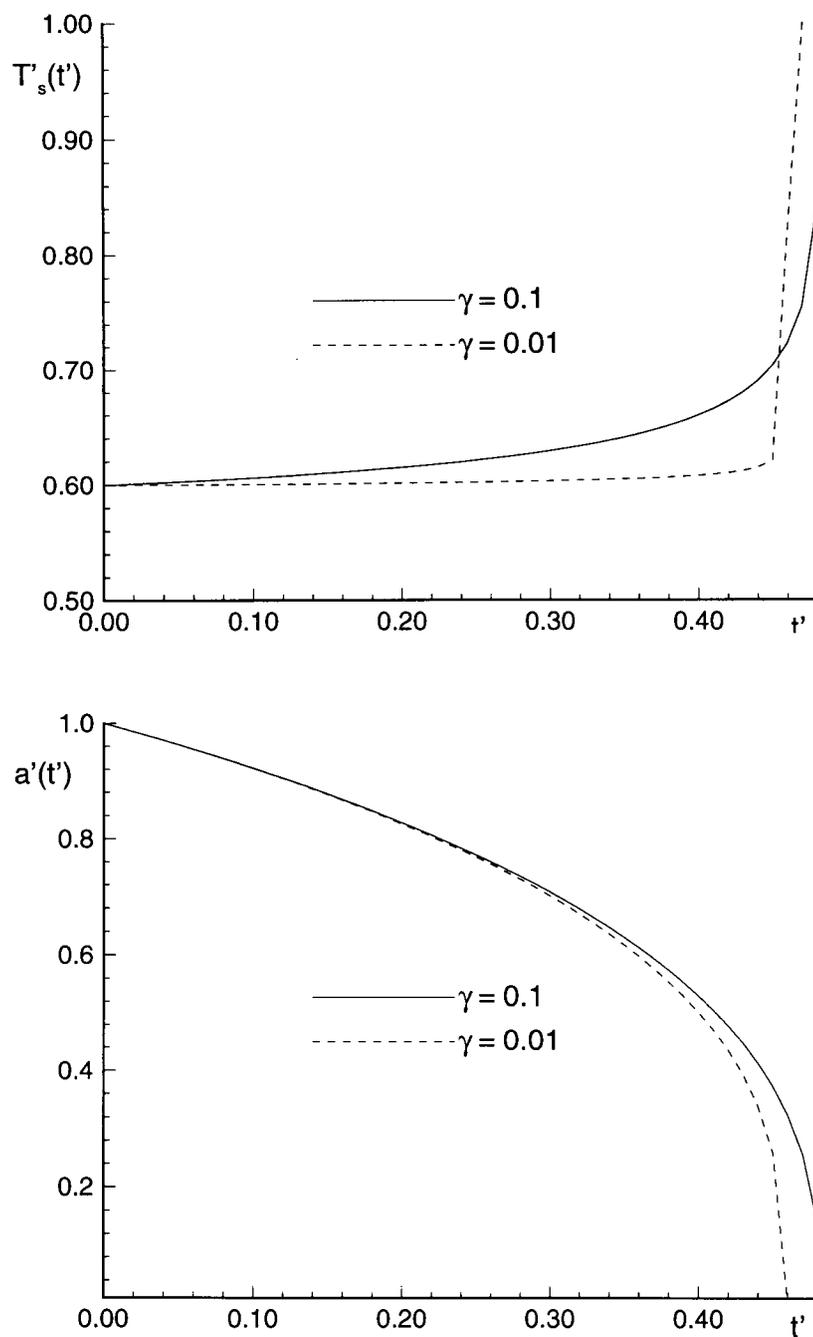
Figure 9: $T_s(t')$ and $a'(t')$ for $\nu = 0.3$ and $T'_R = 0.6$ with re-radiation.

Note that while the detailed results are not given here numerical experiments with the model have led to the following conclusions

1. The effect of particle re-radiation is to increase the roasting time by a factor of 1.4 from that obtained earlier in the zero re-radiation situation. In spite of this when re-radiation is accounted for, the *scaled* roasting time is a very weak function of γ over the γ range of interest. Thus the roasting time is accurately inversely proportional to heating rate, and is given by

$$t_r = 0.5t_0 = 0.5\frac{R\rho b}{\epsilon\sigma T_s^4} \text{ for } T_R' \approx 0.6,$$

   under the operating conditions envisaged. The effect of the parameter T_R' on the roasting time is much more marked with a two fold increase resulting from an increase in T_R' from $0.6 \rightarrow 0.9$.

2. As for the non-re-radiation case the surface temperature of the particle increases at first slowly and then rapidly. In this case, however, T_s remains finite with $T_s' \rightarrow 1$ as $a' \rightarrow 0$. The particle reaches thermodynamic equilibrium with its radiative environment, as required by the physical setup being examined.

3. The effect of γ on the surface temperature of the particle *is* marked. The temperature rise above the reaction temperature is of the order of γ throughout most of the roasting process but then increases rapidly as $a(t) \rightarrow 0$ as the reaction surface area shrinks to zero.

It's clear from the above that if melting is to be avoided then it may be necessary to operate in the $T_R' \rightarrow 1$, γ small range and carefully avoid the *very rapid* changes that occur when roasting is almost complete.

7. Conclusion

Estimates of the conversion times based on the simple models developed at the Study Group tend to support the claims made by Midrex about the Fastmet^{TM} process. The pellet model gives a shorter estimate for the conversion time and it may well be that a single pellet sitting on top of the layer of pellets would be converted in this time whereas the whole layer conversion would take of the order of 6–7 minutes. However there is a need for better estimates of many of the critical parameters such as thermal conductivity, porosity, heats of reaction and the heat loss to the grate.

Further work is also needed on the optimal thickness of the pellet layer and some preliminary work on layers of pellets has already been undertaken but is not described in this report.

Acknowledgments

References

T. Akiyama, H. Ohta, R. Takahashi, Y. Waseda and J. Yagi, "Measurement and modeling of thermal conductivity for dense iron oxide and porous iron ore agglomerates in stepwise reduction", *ISIJ International* **32** (1992), 829–837.

J.M. Hill and J.N. DeWynne, *Heat conduction* (Blackwell, Scientific Publications, Oxford, 1987).

B–H. Huang and W–K. Lu, "Kinetics and mechanisms of reactions in iron/coal composites", *ISIJ International* **33** (1993), 1055–1062.

J.A. Lepinski, "The FASTMET direct reduction process", *52nd Ironmaking Conference Proceedings*, 349–352. Meeting held at Dallas, Texas March 28–31, (1993).

D.R. Lide, Ed., *Handbook of chemistry and physics, 73rd Edition* (CRC Press, 1992).

Y.S. Touloukian, *Thermophysical properties of matter* (Plenum, 1970).

T. Usui, M. Ohmi, S. Hirashima and Y. Oshima, "Kinetic analysis on the rate of reduction of single particles and fixed beds of sinter with CO–CO2–N2 and H2–H2O–N2 gas mixtures", *Proceedings 6th Process Technology Conference*, Fifth International Iron and Steel Congress, Washington (1986), 545–553.

T. Usui, M. Ohmi, S. Kaneda, M. Ohmasa and Z. Morita, "Re–examination of methods of kinetic analysis on the rate of stepwise reduction of a single sinter particle with CO–CO2–N2 gas mixture", *ISIJ International* **31** (1991), 425–433.

R.D. Walker, *Modern Ironmaking Methods* (Institute of Metals, London , 1986).