Mathematical Modeling of the Melting Rate of Metallic Particles in the Electric Arc Furnace

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A computational fluid dynamics model coupled to a lagrangian model of melting/solidifying particles has been developed to describe the melting kinetics of metallic particles in an industrial Electric Arc Furnace (EAF), assuming that liquid steel occupies the entire computational domain. The metallic particles represent Direct Reduced Iron (DRI). The use of two previous models, an arc model and a fluid flow model has made possible to evaluate the melting rate of injected DRI in a three phase-EAF, evaluating the influence of the initial particle size, the initial DRI temperature, feeding position, feeding rate, arc length and some of the metallurgical properties of DRI. The frozen shell formed in the early stage of the melting process has also been evaluated in this model.

KEY WORDS: DRI melting; CFD; melting rate.

1. Introduction

Direct Reduced Iron (DRI) is an important feedstock in Electric Arc furnaces (EAF). Its melting and dissolution processes involve heat, mass and momentum transfer, however in addition to the complex physical and chemical composition of DRI, the melting and dissolution phenomena also involve a multiphase system, which comprises liquid slag, liquid steel, evolving gases and solid particles. A full understanding of the DRI melting process remains today, as a challenge.

The melting process of direct reduced iron (DRI) is similar to the dissolution kinetics of ferroalloys in steelmaking. Lee et al.1) outlined the influence of several process variables on the dissolution kinetics of ferroalloys, in the absence of turbulence, which can be summarized as follows: (i) a shell of frozen liquid is formed around the additions, the thickness of this shell increases as the thermal conductivity of the addition also increases, (ii) the dissolution mechanism depends on the melting point of the addition. When the melting point is lower than that of the steel, the core melts before the shell, in this case the controlling mechanism is by heat transfer, (iii) an increase in the particle size of the addition increases the dissolution time, (iv) the time required for the melting of the frozen shell is much higher than the time required for the core. Seaton et al.2) developed a heat transfer model to compute the temperature profile during DRI melting in liquid steel, neglecting the formation of the frozen shell. They found a low heating rate of the inner radius during the early stage and a high heating rate at the end of the molten process. A higher heat transfer coefficient was associated with higher melting rates.

The first mathematical model on the melting rate of DRI was reported by Elliot et al.3) in 1978. They also evaluated the melting rate of DRI under laboratory conditions in ferrous silicate slags. They found that by increasing both stirring conditions and slag temperature, the thickness of the frozen shell decreases. According with their model, a particle of 10 mm requires approximately 35 s to melt, this time is almost the same time it takes to remelt the frozen shell. They also reported the influence of density and particle size. In small particles (< 5 mm), its density doesn’t affect the melting time, however for large particles (> 10 mm) those particles with a density higher than that of the slag melt faster.

Ehrich et al.4) reported results on the melting rate of sponge iron spheres as a function of initial temperature and particle size, the heat transfer coefficient and thermal diffusivity. A mathematical model was developed by solving the heat flow equation for spherical particles. An important feature of this work was the model validation by immersing dense iron spheres in its own melt. This mathematical model was subsequently reviewed by Zhang.5) One of the most important equations in the model is the boundary condition which describes the heat balance at the solid–liquid interface during the heating of one single particle. In this equation the difference between the convective heat flux entering the interface and the conductive heat flux leaving the interface is equal to the rate of melting or solidification, which depends on the sign of the rate of change of the particle radius (either increasing or decreasing), furthermore, in order to simplify this particular equation it is assumed
that the thickness of the frozen shell is negligible in comparison with the radius of the particle, therefore, in the thermal balance the radius employed is not the radius at the liquid–particle interface but the initial particle radius, as follows:

\[
k_p \frac{dT_p}{dr} = \rho_p \Delta H_m \frac{dr}{dt} + h(T_c - T_p) \quad \text{(1)}
\]

Sato et al.\(^{(6,7)}\) reported laboratory experimental results from the melting of pre-reduced pellets in liquid steel and in molten slags. They found an increase in the melting rate by increasing metallization of pellets and by increasing the temperature of the molten bath, however, once the temperature reaches 1570°C a further increase has no significant effect on the melting rate.

Aboutalebi et al.\(^{(8)}\) reported the influence of particle size, temperature and stirring conditions on the melting rate of metallic particles in a ladle. In this work the formation of the solid shell was neglected. They concluded that the melting rate increases by decreasing the particle size and by increasing both superheat temperature and stirring conditions. Similar results have been reported by Jiao and Themelis\(^{(9)}\) and Ji et al.\(^{(10)}\)

Zhang and Oeters\(^{(11)}\) described a mathematical model to represent the melting process of ferromanganese particles thrown into a steel ladle. They found a short time, less than 1 s, to reach the terminal velocity inside the melt and such velocity was used to compute the heat transfer coefficient. A melting distribution time to represent the melting rate of all particles was used to define the melting time of a variable particle distribution. It was found a higher melting rate as both the terminal velocity and melt temperature increases.

Several works have been reported on scrap melting in Electric Arc Furnaces (EAF). Matson and Ramirez\(^{(12)}\) investigated the melting process of scrap assuming spherical iron particles. Gaye et al.\(^{(13)}\) suggested a maximum scrap size of 120 mm in the converter to avoid unmelted scrap at the end of the blow. Szekely et al.\(^{(14)}\) attributed a key role to carbon dissolved in liquid steel to facilitate scrap melting. Li et al.\(^{(15)}\) used steel bars with various sizes to describe scrap melting.

An integral approach coupling heat, mass and fluid flow phenomena to understand the DRI melting and dissolution processes in electric arc furnaces has not yet been carried out. It is important to point out that most of the previous models reported in the literature deal with numerically solving a transient heat conduction problem with a mobile convective boundary. This approach is able to properly compute both the temperature distribution and the particle radius evolution, however, since the computational domain is a single solid sphere of variable radius, the convective boundary condition is oversimplified and consequently the local temperature and stirring conditions of the melt are not taken into account. It is the objective of this work to present some results describing the melting process of iron particles in its own melt in an industrial three phase EAF including the local temperature and stirring conditions. This new approach losses some details in the computation of the DRI melting kinetics, however its main advantage is the coupling of the local temperature and stirring conditions in the furnace under specific process parameters with the melting kinetics of DRI.

2. Description of Mathematical Model

Frame of Reference: The simulation is restricted to two phases; the solid to be melted and the liquid phase. The two phase system can be described by establishing an Eulerian frame of reference to describe the fluid flow and the heat transfer in the continuous phase by solving the turbulent Navier–Stokes, the continuity and the energy conservation equations, additionally, a Lagrangian frame of reference is used to track the pellets trajectories by using the Newton’s second law of motion and allowing exchanges of momentum and heat between the liquid and the particle. The particles are allowed to undergo phase transformations such as melting or solidification. This Eulerian–Lagrangian approach is able to analyze the two phase system and also the time to solve the system of equations is shorter than the Eulerian–Eulerian approach.

The two-phase model to simulate the melting behavior of solid particles in an electric arc furnace bath is composed of three sub-models, (a) an arc model, (b) an Eulerian fluid flow model and (c) a Lagrangian melting model. The first two models have been reported elsewhere\(^{(16,17)}\) and only a brief description will be outlined below. An important feature of these models is the computational domain shown in Fig. 1, which considers an industrial size, 3-phase electric arc furnace of 220 tons.

Arc Model: This model\(^{(16)}\) is used to define the instantaneous electric power delivered by each phase in a 3-phase electric arc furnace, as a function of the main electrical parameters, such as arc length and arc voltage. The arc model is based on the Channel Arc Model modified by Larsen.\(^{(18)}\)

Fluid Flow Model: This model\(^{(17)}\) was developed to compute velocity and temperature fields in the entire com-

![Fig. 1. Computational domain.](image-url)
putational domain totally filled with liquid steel. It was assumed that the main driving forces are due to buoyancy forces. Localized heating is quantitatively described by the model. For a given set of electrical parameters, the instantaneous electric power is used as boundary condition in this model.

Melting Model: This model defines the melting rate of DRI pellets in the electric arc furnace as a function of several process variables. In order to simplify the computations, the following assumptions are made.
- Free surface (no slag).
- Constant thermo-physical properties.
- Walls at constant temperature of 1 500°C.
- Radiation from the walls and roof is not taken into account.
- Steady state conditions in the flow.
- Porous iron spheres of low density and uniform size to simulate DRI.
- Liquid steel is the continuous phase and DRI the dispersed phase.
- Uniform temperature in DRI particles.
- Temperature is uniform across the section of a single pellet but this temperature changes with time.

Governing Equations: The equations take into consideration heat and momentum exchange among the two phases as well as the formation of a frozen shell around the solid phase at the beginning of the melting process.

2.1. Equations of Motion

The momentum equation associated with each particle is given by the following expression
\[
\frac{dm_p}{dt} = \frac{4}{3} \pi R_p^3 (\rho_p - \rho_l) g + 2 \pi R_p C_D \rho \left[ U_C - U_p \right] \]
- \[C_A \frac{4}{3} \pi R_p^3 \rho \frac{dU_p}{dt}\] ........(2)

This is the second law of motion, i.e., mass times acceleration equals all forces acting on the particle. The term on the left side of the previous equation represents the rate of change of momentum associated with the particle. The three terms on the right side correspond to the various forces acting on the particle; buoyancy force, drag force and force associated with the added mass.

The instantaneous velocity of the particle is given by the following equation.
\[
U_p = \frac{dx_p}{dt} \] .................(3)

Where: \(x_p\) represents the particle position vector, \(U_p\) the particle instantaneous velocity, \(m_p\) is the mass of each particle, \(R_p\) is the particle radius, \(C_D\) is the drag coefficient, \(C_A\) is a coefficient of added mass, \(g\) is the gravity constant, \(\rho_p\) and \(\rho_l\) represent the densities of particle and liquid, respectively. \(U_C\) represents the instantaneous velocity associated with the liquid continuous phase, \(U_C\) is the time averaged velocity of liquid and \(U_C^*\) is the fluctuating velocity of the liquid due to the turbulence. These three velocities are related by the following expression.

\[
U_C = U_C + U_C^* \] ..................(4)

2.2. Equation of Thermal Energy Conservation

The change of temperature in the solid with respect to time is obtained by an energy balance, included in the subroutine GENTRA of the commercial code Phoenics, which assumes that the particle temperature changes with time and the fraction of solid remaining in the particle, \(T(t)\), but at any instant, the temperature is uniform in the whole particle.

\[
m_p C_p \frac{dT_p}{dt} = m_p \Delta H_m \frac{df_s}{dt} + h(T_p - T_v) \] ..................(5)

where: \(m_p\) is the mass of the particle, \(C_p\) is the heat capacity of the particle, \(T_p\) and \(T_v\) represent the temperatures for the particle and the surrounding liquid, respectively, \(\Delta H_m\) is the latent heat of solidification, \(f_s\) is the fraction of solid phase remaining in the particle, \(h\) is the convective heat transfer coefficient.

In the previous equation, the left hand side term represents the accumulation term. The two terms on the right hand side represent the amount of heat released or absorbed due to solidification or melting and the heat transfer exchange from the surrounding liquid steel to the particle. At the beginning of computation the Lagrangian model computes the size of the frozen shell. Once the shell is known, the particle size, \(R_p\), and mass \(m_p\) remain constant. The melting rate is now controlled by the solid fraction which initially is unity and when melting has been completed is zero, finishing with a fully liquid particle of mass \(m_p\). A particle size \(R_p\) and a temperature equal to the liquidus temperature of the particle. In order to describe the melting rate of the particle, the radius of the remaining solid phase is directly related to the fraction of solid (\(f_s\)). This calculation differs from previous models where only the solid particle was considered in the computational domain and as melting occurs the particle size decreases. Although the former computational approach accurately describes the instantaneous particle radius and temperature profile within the particle, convection is oversimplified, only treated as a boundary condition for a single solid sphere. On the other hand with the approach followed in our work, there is an oversimplification in the radius and temperature evolution of the particles, however the convection governed by the heat transfer coefficients are included based on local bath temperatures, turbulence and stirring conditions prevailing in a more realistic multiparticle system. The convective heat transfer coefficient is computed based on the Ranz–Marshall equation
\[
h = (2 + 0.6 \text{Re}_p^{0.5} \text{Pr}_p^{1/3}) \frac{k_s}{D_p} \] ..................(6)

Where: \(\text{Re}_p\) and \(\text{Pr}_p\) represent the Reynolds number and Prandtl number for the particle, respectively, \(k_s\) is the thermal conductivity for liquid steel and \(D_p\) is the diameter of the particle.

The drag coefficient, \(C_D\), is taken from the correlation provided by Clift, Weber and Grace, for spherical particles and Reynolds numbers lower than \(3 \times 10^7\).
The solid fraction of the particle is determined from the lever’s rule:

\[ f_s = \left( \frac{T_l - T_p}{T_l - T_s} \right)^n \]  

Where \( f_s \) is the solid fraction, \( T_l \) is the particle’s liquidus temperature, \( T_p \) is the particle’s solidus temperature, \( T_s \) is the particle temperature, and \( n \) represents a solidification index (a value of one was employed in the simulations).

3. Model Results and Analysis

The results reported in this work correspond to those employed in the operation of an industrial electric arc furnace of 220 ton of nominal capacity with the following general dimensions: top radius of 3.474 m and bath depth of 1.5 m. Steel is produced from 100% DRI, which is continuously injected into the furnace at a predefined feeding rate.

The variables investigated and their range are as follows: particle size (1–35 mm), porosity (30–90%), density (2000–9000 kg/m³), solid’s feeding rate (600–5400 kg/min), solid’s temperature (25–1000°C), inlet position, arc length (25–45 cm). A standard case was defined for the set of conditions: particle size, 12 mm; porosity, 0%; feeding rate, 3500 kg/min; solid’s temperature, 45°C; voltage phase, 1210 V; arc length, 45 cm. Due to software limitations, a fixed amount of particles was defined in 500.

3.1. Frozen Shell Formation around DRI Particles

The results displayed in Fig. 2 correspond to the standard case and various arc lengths. This figure indicates the growth of a frozen shell around DRI particles as soon as they came in contact with liquid steel. It is observed that the thickness of the frozen shell is independent of arc length. In this case, the particle size increases by about 41%. The total melting time is in the range of approximately 12–17 s for a particle size of 12 mm as a function of arc length. As arc length increases the electric power increases and consequently the temperature of liquid steel also increases which yields faster melting rates, therefore, in order to increase the melting rate an operation with long arcs is recommended. It can also be observed the importance of the frozen shell formation. Its formation process is instantaneous; however, its remelting process takes approximately 50% of the total melting time. This result reinforces the importance of including the frozen shell formation stage during the melting process. Engh et al. reported a theoretical analysis which concluded that at high Nusselt numbers (strong agitation) and high melt superheat, the frozen shell formation could be ignored, but according with the results reported in this work, ignoring this shell represents 50% of error in the melting time. This difference is probably due to the fact that in multiparticle systems energy balances are totally different than in single particle systems where the liquid temperature is assumed to be constant while in a real process, temperature gradients above 100°C may exist, furthermore, the strong agitation assumed by Engh is not valid in the electric arc furnace. This is a reactor with low stirring conditions and large thermal stratification.

The non realistic flat profile of the shell formed around the solid particle implies instantaneous formation and an extremely low melting rate in the initial stage of the melting process of the frozen shell. This abnormal behavior may be due to the oversimplification of assuming a uniform temperature distribution in the whole solid sphere.

The effect of the initial particle size on the melting rate and thickness of the frozen shell is shown in Fig. 3. This figure indicates that when the initial particle size increases, the mass and diameter of the frozen shell also increases and consequently the melting time also increases. When sponge iron is produced, exhibits a particle size distribution which ranges from powder to large particles. Typically, almost 40–50% of the total corresponds to particles of 12.5 mm. In general, more than 95% of the total covers a range from 5–15 mm. Particles below 6.3 mm are considered fines and particles above 16 mm are considered too large particles.
3.2. Melting Rate as a Function of the Initial Particle Size

Figure 4 shows the melting rate as a function of the initial particle size and arc length. It is observed that an increase in the initial particle size increases the melting time, for instance, particles of 12 mm melt in less than 17 s, but when the particle size increases up to 20 mm, the melting time increases above 45 s. Elliot et al. computed longer melting times for the same particle size; this difference is due to differences in the liquid phase employed in both cases. They immersed solid particles in liquid slag and in this work the solid particles were immersed in liquid steel. Smaller melting times are expected using a liquid phase of higher thermal conductivity. It is important to mention that, in spite of model predictions of faster melting times when the particle size is smaller, that the addition of fines is an extremely inefficient practice, since most of the fines injected do not reach the required momentum to penetrate into the liquid and therefore end up trapped by the off-gas exhaust system or leave the furnace floating over the slag. In practice, particles smaller than about 6 mm are considered fines which should be avoided.

3.3. Melting Rate as a Function of Arc Length

The previous figure also shows that when arc length increases, produces a decrease in melting time, with a more pronounced effect when the particle size is above 10 mm. Figure 5(a) describes in more detail the influence of this variable, confirming the advantages of increasing arc length. An increase in the transformer secondary voltage increases arc length and also the electric power for melting, consequently, more thermal energy is supplied to the bath and thus enhancing the melting rate of DRI. Figure 5(b) shows the relationship between the arc power delivered to the bath as a function of the arc length for various arc voltages. In other words, in this model an increment in arc length corresponds to increasing the melt superheat. A long arc operation can be detrimental to both, the furnace refractory due to the formation of severe hot spots, and the thermal efficiency, if the radiation is out of control, however, the problem can be solved working with foamy slags.

3.4. Melting Rate as a Function of the Initial DRI Temperature

Figure 6 shows the effect of the initial temperature of DRI on melting time. It is observed that the initial temperature has a marked effect on melting time. The melting rate increases as the initial temperature of DRI particles also increases. This will in turn decrease tap-to-tap time, promoting a higher productivity. Electric energy consumption would also be reduced with the associated savings. Figure 7 reports the influence of the initial temperature of DRI on melting rate for the standard case. It is observed a higher melting rate as the initial temperature of DRI increases.
behavior is due to the uniform temperature assumption associated with the Lagrangian model.

As the initial temperature of DRI increases, electric energy consumption in the electric arc furnace decreases, evidently, a higher initial DRI temperature yields multiple benefits. Current technologies for DRI production are capable to provide with hot DRI. In general, temperatures in the order of 600°C have been reported for hot DRI.

Figure 8 shows the effect of the initial DRI temperature on the average temperature of the molten bath. Increasing the initial DRI temperature provides a higher amount of sensible heat, therefore, the average temperature of the molten bath increases. This behavior can be used to increase the solids flow rate to keep the temperature of the molten bath at a constant temperature. The natural trend when the solids flow rate is increased, at a constant temperature, is a decrease in the average temperature of the molten bath, as shown in Fig. 9.

3.5. Melting Time as a Function of the Position of DRI Feeding

In order to decrease the melting time, the optimum position should provide for conditions of higher heating rates of the solid. The influence of position of the inlet stream of solid particles into the electric arc furnace is shown in Fig. 10. According with the model results the injection of DRI in the center of the pitch circle is the optimum position which yields the shortest melting time, this zone corresponds to the hottest zone in the furnace. In practice, the
typical feeding position of DRI is in the position number 1, which is close to the hottest zone.

3.6. Melting Time as a Function of the Physical Properties of DRI

DRI is a material highly heterogeneous, both physically and chemically, in addition to this, its metallurgical properties are not well known, in particular its thermal properties. In the present simulations, four properties were chosen to evaluate the influence of those properties on the melting time. Figure 11 shows the influence of heat capacity. As the heat capacity increases also increases the melting time. This is consistent with the definition of heat capacity. As the heat capacity increases, it also increases the amount of heat required to increase its temperature. Figure 12 shows the influence of DRI thermal conductivity on melting time. Experimental data on thermal conductivity of DRI was reported by Gudenau et al.\textsuperscript{25} indicating values in the range from 2–5 W/m K, for the temperature range from 200–800°C. The thermal conductivity of DRI increases as temperature increases. This increment in thermal conductivity has positive effects on higher melting rates. The simulations from the model suggest a strong influence of the thermal conductivity on the melting time. Thermal conductivity can be further increased by increasing DRI metallization and decreasing porosity. The influence of porosity on melting time is shown in Fig. 13. DRI is a very porous material, ranging from 50–70%. The model indicates a negative influence of porosity on melting time. As porosity increases the melting time also increases.

4. Model Validation

In order to validate the mathematical model of this work, the experimental results reported by Ehrich et al.\textsuperscript{4}\textsuperscript{a} as well as model predictions reported by Elliot et al.\textsuperscript{3}\textsuperscript{a} will be employed. Figure 14 describes the melting time of one particle of 10 mm in diameter and the surface temperature of this particle. The current model defines a melting time of approximately 12 s. The surface temperature reaches approximately 1 800°C. This high temperature results for the standard case operating at the highest voltage. For the same particle size, Elliot defined a melting time of approximately 35 s. The results are consistent. Elliot immersed the particles in molten slag and the current model involves liquid steel. The higher thermal conductivity of solid steel which forms the frozen shell is responsible of higher melting rates.

In order to compare with the experimental values from Ehrich et al.,\textsuperscript{4}\textsuperscript{a} the arc length in the current model was adjusted to yield an average temperature of 1 600°C, which allows similar conditions for the melting rate of 15 mm particles. The results are shown in Fig. 15. It is observed the experimental data are in good agreement with both models. A mayor drawback in previous works is the poor knowledge on the convective heat transfer coefficient which excludes real furnace fluid flow conditions. This value has been estimated based on empirical correlations, however, in the current model, a much better and realistic estimation of those
coefficients are made due to the computation of velocity, turbulence and temperature fields in the entire computational domain.

5. Conclusion

A two phase Eulerian–Lagrangian mathematical model describing the melting rate of metallic particles in liquid steel in an electric arc furnace has been reported. Operating with smaller particles, injected at high temperatures and with a large superheat has been confirmed by the current model. Furthermore, it has also been found that in order to increase the melt superheat that working with long arcs will increase the heat supplied for melting and that higher feeding rates can be used, also, the feeding position affects the melting rate as well as the metallurgical properties of the DRI. DRI with higher metallization has a higher thermal conductivity, increasing its melting rate. DRI porosity negatively affects the melting rate.

The frozen shell period plays a large role in the melting rate of DRI, representing almost 50% of the total melting time. The thickness of this shell increases by increasing the initial particle size.

The melting time of metallic particles in liquid steel is shorter in comparison with the case of melting in slags, this due to the higher thermal conductivity of the frozen shell.

**Nomenclature**

<table>
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<tr>
<th>Symbol</th>
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<tr>
<td>$T$</td>
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<tr>
<td>$t$</td>
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<td>Distance</td>
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<td>$U$</td>
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<td>$\Delta H$</td>
<td>Latent heat of solidification</td>
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<td>$\rho$</td>
<td>Density</td>
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**Subscripts**

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<td>$p$</td>
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<td>$c$</td>
<td>Continuous phase (liquid steel)</td>
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<td>$s$</td>
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<tr>
<td>$l$</td>
<td>Liquidus</td>
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