Modeling of a DC Electric Arc Furnace—Mixing in the Bath

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A mathematical model was developed to describe fluid flow, heat transfer and electromagnetic phenomena in the bath region of a Direct Current Electric Arc Furnace (DC-EAF). The different effects on the steel bath from the arc, a layer of slag on the top of the steel, and the injection of argon gas from the bottom, are represented using three different numeric approaches and analyzed in terms of fluid flow, heat transfer, and temperature stratification in the steel bath. Additionally, a sensitivity analysis was performed to explore the effect of the main process parameters and design variables of the process, such as furnace dimensions, arc conditions, and anode configurations. It was found that in the absence of gas injection, the electromagnetic body forces dominate the fluid flow in the bath region overcoming the opposite effects of buoyancy and shear from the arc. Injection of gases homogenizes the melt improving mixing, while the effect of the slag is to decrease mixing in the bath. Regarding the process analysis, the model showed that the best mixing and the best energy optimization from the arc are achieved when the geometry of the furnace presents the highest aspect ratio. Similarly, short arc lengths and high arc currents are beneficial for mixing. However, these improvements in mixing could be detrimental for the bottom refractory of the furnace because of the direct exposure of the hot metal coming from the arc attachment zone at the bottom wall. Then, the anode configuration can be designed to avoid excessive damage to the refractory.

KEY WORDS: modeling; mixing; fluid flow; heat transfer.

1. Introduction

The Electric Arc Furnace (EAF) process has gained increasing acceptance in the steel production and currently this process represents almost 40% of the total crude steel production in the world. Currently, there are two alternative technologies in the EAF process, i.e., the Direct Current (DC-EAF) and its predecessor Alternate Current system (AC-EAF). It has been claimed that the DC system reduces the energy and electrode consumption, as well as the level of noise. However, it is now accepted that the major advantage of the DC furnace in comparison to the AC system is the prevention of the flicker effect (i.e. the DC arc is more stable). Currently, the DC technology covers approximately 70% of the new EAF being commissioned.

The EAF process has undergone many improvements since the process first appeared in the late 1800’s. These improvements have involved technological changes (mainly on empirical basis) in the practice, with the objective of solving the major concerns of the steelmaker, i.e. reduce the energy, electrode, and refractory consumptions, as well as to increase productivity. Actually, the adoption of a DC system constitutes by itself a technological improvement to the process introduced in the 1980’s. However, the levels of efficiency in the EAF are approaching an asymptotic behavior and it has become evident the need for more fundamental understanding to further impact the EAF efficiency. Particularly, the understanding on the metallurgical operations of the furnace, based on first principles, are the less known aspects of the operation.

In the search for this fundamental knowledge, the first attempt to describe fluid flow and heat transfer in the bath region as influenced by the arc was given by Szekely and McKelliget using the turbulent Navier–Stokes, turbulent energy conservation and Maxwell equations in both the arc and bath regions. They were the first to predict the contributions of the different mechanisms of heat transfer from the arc to the bath. They also studied fluid flow and temperature stratification under the different driving forces for momentum transfer (buoyancy, electromagnetic and shear from the arc). However, their highly simplified arc model definitely restricted the accuracy of the bath calculations, and they were unable to represent gas injection or the presence of a slag phase. Kurimoto et al. presented a mathematical model to predict fluid flow patterns and temperature distributions in the bath region of a DC-EAF under the effect of electromagnetic body forces. However, the presence of the arc was neglected and therefore, the top boundary conditions were oversimplified. Similarly to Kurimoto, Bendzsak represented the bath region of a DC-EAF without considering the representation of the arc region. Recently, Liping Gu et al. published physical and mathematical models of the fluid flow in the steel bath considering specific operations in the EAF, such as gas bubbling injection, the use of oxy-fuel burners, and the effect of carbon.
boil on fluid flow. Experimentally, Deneys and Robertson\(^9\) built a laboratory scale DC-EAF to study the effect of the arc in slag cleaning processes. In their system they studied the fluid flow phenomena on the bath surface due to the arc shear using a video photography technique. Finally, Kang\(^10\) and Murphy\(^11\) built experimental setups to study the effect of electromagnetic body forces on fluid flow patterns and turbulence structure using a small Woods metal system. By using hot-wire anemometry, they were able to report useful data on velocity fields and turbulent parameters characteristics.

It is clear that only a few attempts to model the DC-EAF operations have been reported in the past and that no radically new contributions have been made to this field of modeling since the work of McKelliget and Szekely more than 25 years ago.

In this work, the physics involved in the DC-EAF process, i.e. heat transfer, fluid flow and electromagnetic phenomena are addressed to study the system. In the approach adopted in this paper, the DC-EAF has been divided in two regions, i.e., the arc and the bath region. The computation of the arc region presented previously,\(^{12}\) provides the arc bath-interactions such as heat, current, and shear stress to the bath region. These arc-bath interactions are used in this paper to prescribe the boundary conditions required to represent the bath region.

The model involves the simultaneous solution of Maxwell's equations for the electromagnetic field, and the turbulent fluid flow and heat transfer equations. In solving the bath region it is assumed that the arc-bath interactions are dominated by the behavior of the arc. In contrast to previous modeling investigations, this work relaxes some critical assumptions and provides a more realistic and comprehensive representation of the system. Part of the merit of this work stands on the highly sophisticated arc model presented in our previous publication,\(^{12}\) which provides realistic representations of the arc-bath interactions. Furthermore, due allowance is made to represent and analyze the effect of gas injection, the presence of a slag layer in the bath and the differences in anode configurations. Finally, a detailed analysis is carried out to examine the effect of process parameters (e.g., arc current, arc length, bath dimensions, anode arrangements, etc.) on the behavior of the furnace (i.e., heat transfer to the bath, heating efficiency, mixing in the bath, etc.).

2. Mathematical Model of the Arc Region

In this paper only the arc-bath interactions are presented. These results obtained with the arc model (see Ref. 12) are linked as the boundary conditions to the bath model described here. Figure 1 shows an example of arc bath interactions showing the heat flux (a), the current density (b), and the shear stress (c) at the bath surface for a 40 kA of arc current and 0.25 m arc length.

3. Mathematical Model of the Bath Region

Figure 2 presents a schematic simplified representation of the bath region. The arc region is also placed above the cylindrical furnace container for completeness of the picture. The arc provides heat, current, shear stress, and pres-
sweat at the top bath surface. The bath phase in the refining stage is composed of liquid steel, liquid slag on top of the steel and gases evolved from carbon boil or injection from the bottom through porous plugs. Circulation of the bath is promoted by the electromagnetic forces produced by the passage of the current and the self-induced magnetic field, by shear stress at the bath top surface and by buoyancy due to temperature gradients inside the melt. Heat is mainly transferred from the arc as described in. Heat is also generated inside the melt by Joule effect due to the pass of current and the heat leaves the system through the furnace walls and by radiation from the melt top surface to the furnace wall panels and roof. In addition to these heat and momentum transfer phenomena, mass transfer is also critical in the bath region, where solute concentrations are determined by thermodynamics and kinetics of the steel-slag, steel-gas chemical reactions taking place.

Three different bath models are proposed in this paper to represent different physical conditions of the bath region described above: i) a model considering a single steel phase occupying the entire domain, ii) a two-phase model to represent the gas injection of argon into steel (gas–liquid), and iii) a two phase model representing a layer of slag on the top of the steel (liquid–liquid).

### 3.1. Single Phase (Liquid Steel) Mathematical Model

In the mathematical representation of the bath region a general case dealing with a single phase is first described. The alternative formulations required to represent gas injection and the additional slag phase are discussed subsequently.

#### 3.1.1. Assumptions and Governing Equations

The simplest, single-phase model of steel bath is represented on a cylindrical axi-symmetric coordinate system in which the arc-bath interface is assumed flat. The physical properties of all phases are independent of temperature and thus, a zero potential value is assigned there, while the good conductor of the current and constitutes the anode, net current loss at the top bath surface. The bath phase in the refining stage is composed of liquid steel, liquid slag on top of the steel and gases evolved from carbon boil or injection from the bottom through porous plugs. Circulation of the bath is promoted by the electromagnetic forces produced by the passage of the current and the self-induced magnetic field, by shear stress at the bath top surface and by buoyancy due to temperature gradients inside the melt. Heat is mainly transferred from the arc as described in. Heat is also generated inside the melt by Joule effect due to the pass of current and the heat leaves the system through the furnace walls and by radiation from the melt top surface to the furnace wall panels and roof. In addition to these heat and momentum transfer phenomena, mass transfer is also critical in the bath region, where solute concentrations are determined by thermodynamics and kinetics of the steel-slag, steel-gas chemical reactions taking place.

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#### 3.1.2. Electromagnetic Problem and Its Coupling with the Heat and Momentum Equations

The electromagnetic body forces constitute the coupling between the electromagnetic phenomena and fluid flow (Eqs. (1a) and (1b)). The coupling between the electromagnetic phenomena and heat transfer is through the Joule heating source (Eq. (1c)). Finally, heat transfer and fluid flow phenomena are coupled through buoyancy forces expressed by the Boussinesq approximation (Eq. (1d)):

\[
F_r = -J_r B \\
F_z = J_z B \\
Q_{\text{Joule}} = \frac{J_z^2 + J_r^2}{\sigma} \\
F_{\text{Buoyancy}} = -\rho \gamma_i g (T - T_o)
\]

where \( \rho \) is the steel density at the reference temperature \( T_o \), \( g \) is the gravitational vector, \( \gamma_i \) is the thermal coefficient of volume expansion for steel, \( T \) is the melt temperature, \( \sigma \) is the electric conductivity of steel, \( F_r \) and \( F_z \) are the axial and radial components of the electromagnetic body forces respectively, and finally, \( J_r \) and \( J_z \) are the axial and radial components of the current density vector respectively.

#### 3.1.3. Boundary Conditions

The boundary conditions reflect zero velocities and zero turbulence values at the walls. The link between the laminar region (adjacent to the wall) and the fully turbulent region is given by the wall function approach. For the electromagnetic representation, the bottom wall is assumed to be a good conductor of the current and constitutes the anode, and thus, a zero potential value is assigned there, while the lateral wall does not conduct electricity. At the symmetry axis, all variables have zero flux conditions. Finally, at the top surface, the heat flux, the shear stress and the current from the arc calculations are introduced as boundary conditions for the energy, radial momentum and potential equations, respectively. Also at the free surface, steel is allowed to lose heat by radiation. Table 1 presents all boundary conditions based on the geometry and symbols employed in

| Location          | Radial velocity \( v_r \) | Axial velocity \( v_z \) | Steel temperature \( T \) | Electric potential \( \phi \) | Turbulent kinetic energy \( k \) | Energy dissipation rate \( e \) |
|-------------------|--------------------------|------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Symmetry axis     | 0                        | 0                      | 0                        | 0                        | 0                        | 0                        |
| Bottom wall       | 0                        | 0                      | \( T_{\text{wall}}=1773 \text{ K} \) (convective heat with non-equilibrium wall function) | \( \phi = 0 \) (non-equilibrium wall function) | \( \frac{\partial k}{\partial r} = 0 \) | \( \frac{\partial e}{\partial r} = 0 \) |
| Lateral wall      | 0                        | 0                      | \( T_{\text{wall}}=1773 \text{ K} \) (convective heat with non-equilibrium wall function) | \( \frac{\partial \phi}{\partial r} = 0 \) (non-equilibrium wall function) | \( \frac{\partial k}{\partial r} = 0 \) (wall function) | \( \frac{\partial e}{\partial r} = 0 \) (wall function) |
| Top surface       | \( \tau \) from arc model | 0                      | \( \theta_{\text{arc}} = \theta_{\text{arc}} = \alpha \sigma \) | \( \frac{\partial \phi}{\partial r} = \frac{J_{\text{arc}}}{\sigma} \) (arc model) | \( \frac{\partial k}{\partial r} = 0 \) (arc model) | \( \frac{\partial e}{\partial r} = 0 \) (arc model) |

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3.1.4. Physical Properties of Steel and Geometric Parameters of the Reactor

A list of the physical properties employed in the calculations for the single steel phase model together with the geometric parameters used is presented in Table 2.

3.2. Gas–Steel Model

When injection of argon gas through a nozzle from the bottom is included in the DC-EAF, the bubbling process makes necessary some modifications to the model previously presented, in order to account for the effect of the bubbles ascending through the melt. Gas injection involves the solution of a complete set of conservation equations for both the gas and liquid phases. Then, the gas-steel system is handled with the Eulerian–Eulerian approach and implemented with the numerical technique called IPSA (Inter-Phase-Slip-Algorithm). Additionally, since the bubbling practice must be eccentric, at specific injection points, the gas–steel system must involve a 3D representation.

3.2.1. Assumptions for the Gas–Steel Model

The model is based on the Eulerian–Eulerian approach to solve the two-phase problem in the bath region, in which the two phases share the same domain. One phase is continuous (liquid) while the other is dispersed (gas). The approach comprises the solution of a complete set of conservation equations for each phase present in the domain. Additionally, the electric potential is associated with the steel, which is the conductive phase, and turbulence is associated to the liquid phase only. Also, all the other assumptions from the single steel phase model apply in this case.

3.2.2. Governing Equations for the Gas–Steel Model

The governing equations for each phase are: Continuity equation, the turbulent Navier–Stokes equations, the turbulent energy conservation equations, the Maxwell equations, the charge conservation equation and Ohm’s law (only on steel, since steel is the conductive phase). The conservation equations for the turbulent kinetic energy, $k$, and the energy dissipation rate, $\varepsilon$, associated with the standard $k$–$\varepsilon$ turbulence model. Finally, it is important to specify that in the IPSA technique only one pressure is solved and both phases share the same pressure.

3.2.3. Interfacial and Special Sources

The same sources described by Eqs. (1a) to (1d) are included in the liquid momentum and energy equations for this model. Additionally, an important momentum source for the gas phase is the buoyancy effect due to the difference of densities between the gas and liquid steel. The link between the two phases is considered at the gas–liquid interface where both phases exchange momentum and heat. Expressions describing the exchange of momentum (friction between gas and liquid) and the heat transfer between the phases are given in Table 3. The interfacial sources in both gas and liquid momentum equations have the same value but opposite sign. The driving force in the friction term is the difference in velocities between the phases, while heat transfer at the interface is driven by temperature differences between the phases. Finally, the additional turbulence generated due to rising of bubbles through the melt is accounted with an extra source terms proposed by Lopez et al., and included in Table 3.

3.2.4. Boundary Conditions

The same boundary conditions applied for the liquid phase in the single-phase model, are valid for all variables in this gas–steel model. However, the gas phase require the setting of additional boundary conditions. At the inlet, vertical velocity for the gas is set according to the gas flow rate and nozzle diameter used in the calculations. Temperature of the gas entering is set equal to the wall temperature. At the top boundary, gas is allowed to escape as soon as it reaches the free surface and the enthalpy carried by the gas leaving is used as a negative source in the energy equation.

3.2.5. Physical Properties of the Phases and Geometric Parameters of the Reactor

Table 4 shows the physical properties of the gas and some geometrical parameters used in the calculations.

3.3. Slag–Steel Model

In this variation to the original single-phase model, the same geometric system presented in Fig. 2 is again considered. However, instead of having only liquid steel, this model represents a two liquid system, where slag of lower density is above the steel. The steel and slag liquids are immiscible and the interface separating them is sharp and well defined due to the differences in density. The sharp interface makes this case totally different from the steel–gas
case where the gas was dispersed into the liquid steel. Because of this fundamental difference at the interface, the problem is treated as a free surface problem between the two liquids. To handle the problem, a marker technique denominated the “Scalar Equation Method” (SEM)\(^{17}\) is implemented. In this technique a one-phase fluid flow simulation is performed and the presence of the top liquid (slag) is determined by the solution of a marker variable. This marker, which has a unit value where steel is present and zero value in slag positions, is allowed to move by convection but is not allowed to diffuse. The track in time of markers determines the free surface position, which is considered to appear where the marker has values between 0 and 1. Then, the maker value is used to assign the physical properties of the corresponding fluids.

3.3.1. Governing Equations, Boundary Conditions and Physical Properties Used

In this model, the conservation equations are solved in transient mode since the marker history is required to track the interface between the two liquids. As initial condition, a layer of slag is placed on the top of the steel and the marker is assigned zero values in the slag region and unit values in the steel region. Initial conditions also include zero velocities and a constant temperature of 1 773 K for both phases. The boundary conditions and assumptions employed in the steel model hold here too. The main difference is that physical properties in each position must be calculated at each time step since their values depend on the phase present at each cell, which in turns depend on the Marker motion defining the interface. Physical properties for a common slag used in DC-EAF are presented in Table 5.

4. Results

The formulations described for the three numerical approaches used to represent the systems: single phase (liquid steel), gas–steel, and slag–steel, were implemented using the commercial computer code PHOENICS version 3.2, in which the electromagnetic formulation was introduced as subroutines.

4.1. Standard Case (Arc Current of 40 kA and Arc Length of 25 cm): General Description

The main characteristics of the bath region are now presented under the effect of the standard arc case of 40 kA of current and 25 cm arc length. The velocity field presented in Fig. 3(a) exhibits a circulation loop in the clockwise direction. The steel presents downward flow near the symmetry axis and upward flow near the lateral wall. The magnitudes of the velocities are large close to the symmetry axis (with a maximum velocity of 1.2 m/s) and small close to the lateral wall. Electromagnetic body forces drive the fluid motion leaving the other two driving forces, i.e., shear from the arc and buoyancy, in a secondary position. Stream lines presented in Fig. 3(b) confirm the circulatory flow pattern followed by the liquid under the effect of the arc, by forming a single clockwise loop, whose center is located closer to the lateral wall and midway between top and bottom surfaces. Figure 3(c) shows the temperature field inside the bath region. The effect of the arc is evident since the highest temperatures are found at the top surface just below the arc (the “arc attachment zone”). In this zone, most of the heat, current, and shear are transferred from the arc to the bath. The velocity field shapes the temperature field. Liquid moving downwards close to the symmetry axis convects liquid enhancing the dissipation of heat received at the top surface from the arc. Temperature gradients are high close to the arc attachment zone but start decreasing as distance from the arc attachment zone increases. A maximum temperature of 1 952 K is found at the center of arc attachment zone, where the highest heat flux is received. A minimum temperature of 1 772 K is located close to the lateral wall and top surface, where the effect of the arc is not important and radiation losses predominate.

| Table 4. Physical properties of argon and numerical values of some geometric parameters of the reactor. |
|---|
| **Physical Properties of Argon Gas** |
| Property | Value |
| Density, \( \rho \) (kg/m\(^3\)) | 1.18 |
| Specific heat, \( C_p \) (J/kg·K) | 520 |
| Viscosity, \( \mu \) (kg/m·s) | 2.0×10\(^{-5}\) |
| Thermal conductivity, \( k \) (W/m·K) | 1.89×10\(^{+6}\) |
| Surface tension Ar-Steel, \( \sigma \) (N/m) | 1.8 |
| **Numerical values of parameters used in the model** |
| Number of nozzles | 3 (symmetrically located) |
| Location of nozzle | @ \( r/R_{bath} = 0.625 \) |
| Nozzle diameter (m) | 0.005 |
| Bubble diameter, \( D_b \) (m) | 0.009 |
| Gas flow rate, \( Q \) (m/s) | 5.0×10\(^{-4}\) |

| Table 5. Physical properties of slag and some geometric parameters of the reactor. |
|---|
| **Physical properties of the slag** |
| Property | Value |
| Density, \( \rho_{slag} \) (kg/m\(^3\)) | 2300 |
| Specific heat, \( C_{p,slag} \) (J/kg·K) | 1137 |
| Thermal volume expansion coefficient, \( v_{slag} \) (K\(^{-1}\)) | 2.7×10\(^{-4}\) |
| Viscosity, \( \mu_{slag} \) (kg/m·s) | 0.43 |
| Thermal conductivity, \( k_{slag} \) (W/m·K) | 0.1599 |
| **Numerical values of parameters used in the model** |
| Thickness of slag layer (m) | 0.05m |

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In the arc attachment zone large gradients of some variables are present and as the distance from the top surface increases, these gradients decrease. To better appreciate this, axial profiles of temperature, potential, and axial velocity along the symmetry axis are presented in Fig. 4. In this plot, potential and temperature axial profiles clearly show that close to the arc attachment zone large gradients exist, but as the distance from the top surface increases, the profiles become smooth.

4.2. Effect of Arc Length and Arc Current on Fluid Dynamics and Heat Transfer in the Bath Region

4.2.1. Arc Length Sensitivity

To examine the effect of the arc length on the bath characteristics, a sensitivity study was conducted running computations of the bath region under electric arcs with a single arc current of 40 kA and five different arc lengths of 0.15, 0.2, 0.25, 0.3 and 0.35 m. Maximum velocities of less than 1.0 m/s are obtained for an arc length of 0.35 m arc length while maximum values of velocity of around 1.5 m/s are obtained for an arc length of 0.15 m. It can be generalized that as the arc length increases the bath velocities decrease, as can be seen in Fig. 5(a), where maximum velocities are plotted as a function of arc length.

Figure 5(b) shows the average temperature in the bath region as a function of arc length. The average temperature can be defined by the following equation:

\[ T_{\text{average}} = \frac{\sum_{\text{cell}} \frac{T_{\text{cell}} V_{\text{cell}}}{V_{\text{total}}}}{\sum_{\text{cell}} \frac{1}{V_{\text{total}}}} \]  

where \( T_{\text{average}} \) is the average temperature, \( V_{\text{cell}} \) and \( V_{\text{total}} \) are the cell volume and total volume respectively, and \( T_{\text{cell}} \) is the cell temperature. The average temperature can be related to the amount of energy being held in the bath region. It has to be remembered that an increase in the arc length is equivalent to an increase in the arc power and consequently more heat is transferred from the arc as the arc length increases. Then, as indicated by Fig. 5(b) an increase in the arc length, for a constant arc current, increases the arc power and also the total amount of energy transferred into the melt and hence more energy is present in the bath region (for a constant volume furnace occupied by steel).

4.2.2. Arc Current Sensitivity

The effect of arc current on arc characteristics is investigated by performing a sensitivity study of the bath region under electric arcs with a single arc length of 0.25 m and four different arc currents of 36, 40, 44 and 50 kA.

Figure 6(a) shows the average temperature in the bath region as a function of the arc current. The figure indicates that an increment in arc current (keeping the same arc length) increases the average bath temperature or enthalpy (which is consistent with the fact that more heat is transferred to the bath from the arc by increasing the arc current). Figure 6(b) shows the maximum velocity as a function of arc current. As arc current increases maximum velocities also increase. This is a very logical consequence, since more current (at the same arc length) is equivalent to
4.3. Effect of the Aspect Ratio of the Reactor on the Fluid Dynamics and Temperature Field

The results presented in this section are devoted to provide the effect of the furnace radius $R_{\text{furnace}}$ and bath depth $H$ on the bath characteristics such as bath temperatures and mixing.

4.3.1. Bath Depth Sensitivity

The effect of the bath depth was analyzed by including computations using bath depths of 0.35 and 0.7 m, but keeping the same furnace radius of 1.5 m with an arc of 40 kA and 0.25 m arc length. Decreasing the aspect ratio $H/R_{\text{furnace}}$ produces a double circulatory loop in the liquid steel bath whose consequence of this complex fluid flow pattern for the smaller bath depth of 0.35 m is a decrease in the mixing process. Figure 7 shows the average temperature (or enthalpy) as a function of the bath volume produced by the increase in bath depth. It can be noted that the energy inside the bath increases as the volume of the melt increases for a constant arc current and arc length (constant arc power). It can be deduced from this figure that the best mixing behavior is promoted by the highest furnace aspect ratio $H/R_{\text{furnace}}$. The fact that mixing improves by increasing the bath depth is important, since it means that increasing the volume of the furnace (enhancing productivity) improves the mixing phenomena.

4.3.2. Furnace Radius Sensitivity

The effect of the furnace radius was analyzed by performing computations using bath depths of 0.35 and 0.7 m, but keeping the same furnace radius of 1.5 m with an arc of 40 kA and 0.25 m arc length. Decreasing the aspect ratio $H/R_{\text{furnace}}$ produces a double circulatory loop in the liquid steel bath whose consequence of this complex fluid flow pattern for the smaller bath depth of 0.35 m is a decrease in the mixing process. Figure 7 shows the average temperature (or enthalpy) as a function of the bath volume produced by the increase in bath depth. It can be noted that the energy inside the bath increases as the volume of the melt increases for a constant arc current and arc length (constant arc power). It can be deduced from this figure that the best mixing behavior is promoted by the highest furnace aspect ratio $H/R_{\text{furnace}}$. The fact that mixing improves by increasing the bath depth is important, since it means that increasing the volume of the furnace (enhancing productivity) improves the mixing phenomena.

4.4. Effect of the Anode Electrode Configuration on Fluid Dynamics and Temperature Field

The last aspect analyzed in the single-phase system is the effect of the anode size on the bath behavior. By default, the whole bottom surface was considered to conduct the electric current. In order to see the effect of the anode surface, the bottom surface is now restricted to the passage of current in certain sections, leading to three different anode surface configurations explored: (a) Anode ring located at a radius of 1.062 m from the center and 0.06 m width. (b) Circular anode at the center with a radius of 0.1 m. (c) Circular anode at the center with a radius of 0.05 m.

Figure 9 shows the potential fields for all of the anode configurations used in the simulations. The change in anode configuration produces different potential lines, which in turn generate different current density fields and electromagnetic body forces. In the case of the anode ring, the potential lines are perpendicular to the bottom surface (no current flows through the wall) except in the position where the ring is present. The small circular anodes restrict the pass of current to a small area, and then, the potential lines, which are concentrated close to the arc attachment zone and then diverge, converge again close to the small anode surface. This configuration leads to two high electromagnetic force zones, i.e., one close to the anode and other close to the arc attachment zone. Both zones are in opposition to decay shown in Fig. 8.

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each other. The result in this rearrangements of electromag-
netic quantities are the velocity fields shown in Fig. 10
where the effect of the anode configuration is evident since
influences the mixing behavior and eventually changes the
flow patterns dramatically. For example, the smallest anode
circular area of 0.05 m produces a complex flow pattern
where the fluid is directed upwards at the symmetry axis,
which contrasts with the downwards movement presented
with the normal bottom anode configuration. The small
anode configuration can be used if the refractory at the bot-
ttom is likely to suffer damage.

4.5. Results of the Gas Injection Model

In this section, results and analysis of fluid flow and heat
transfer in the bath region are presented for the gas–steel
model. First, the isolated effect of gas injection through
three nozzles located at radial distances of 0.94 m from the
center and separated one from the other by 120° for the
same standard case of 40 kA and 25 cm. Then, the other dri-
vng forces are included together with gas injection and
fluid flow and temperature fields are fully described.
Finally, the effect of the gas flow rate on the veloc-
ity and characteristics is presented through a sensitivity study.

4.5.1. Isolated Effect of Inert Gas Injection on Velocity
and Temperature Fields of the Steel (Gas–Steel Model)

Figure 11 shows the computed fluid flow patterns and
temperature distribution on different planes in a 3D domain
for a 3-nozzle gas-stirred EAF system. The domain only
represents a 1/6th. symmetric section of the entire furnace.
Since the purpose of this result is to examine the specific
role of gas injection in determining flow patterns and tem-
perature distributions in the bath, the results shown in the
figure do not include the effects of shear, buoyancy or elec-
tromagnetic forces. Only the heat input from the arc and the
Joule heat effect are considered in the calculation. Under
the conditions of this simulation, the flow patterns indicate
that gas injection can promote reasonable fluid circulation
in the regions close to the wall, with typical velocities of
the order of 0.1 m/s (much higher velocities are appreciated
in the plume region, >1 m/s). In contrast, the central por-
tion of the bath is relatively stagnant. The temperature field
shown in the figure reflects this situation, where a uniform
temperature region is observed near the wall and significant
temperature gradients are predominant in the center of the bath.
It should be stressed, however, that a different mixing situation
in this central region would be expected if electromag-
netic effects were included in the calculation.

4.5.2. Effect of Inert Gas Injection on the Bath Behavior
(Gas–Steel Model)

When gas injection is combined with the additional dri-
vng forces for fluid motion, the relative importance of the
injection and the electromagnetic body forces can be studied.
Figure 12 shows the computed liquid velocity (a), li-
quid temperature (b), and gas volume fraction (c) fields on
different planes in a 3D domain for the 3-nozzle gas-stirred
EAF system presented in the last section. The liquid veloc-
ity field is similar to that presented in Fig. 11, but now the
effect of the electromagnetic stirring is present and then,
close to the symmetry line, the flow motion is dominated by
the electromagnetic body forces. Therefore, the combina-
tion of all forces seems to eliminate dead zones in the reactor.
The temperature field also shows the effect of the elec-
tromagnetic stirring close to the symmetry axis where tem-
perature contours are different from those presented in the
previous case (Fig. 11). In the zone where gas injection pre-
dominates, homogenous liquid temperatures are found
(17 K of temperature difference in this zone). In the gas
volume fraction field, the gas plume formed above the nozzle
is appreciated. The top surface also presents some con-
centration of gas, but the rest of the reactor is almost free of
gas.

4.5.3. Effect of Gas Flow Rate on the Velocity and
Temperature Fields (Gas–Steel Model)

In this section we present a sensitivity study performed
to examine the effect that the gas flow rate has on the veloc-
ty and temperature fields for the gas injection system. The
sensitivity study is obtained considering the standard arc
case (40 kA, 25 cm), for different gas injection flow rates of
5.0×10^{-4} (standard), 2.5×10^{-4}, 1.6666×10^{-4}, 1×10^{-3}
and 1.5×10^{-3} m³/s at each nozzle.
Figure 13 shows the velocity fields obtained when different gas flow rates are employed. As expected, an increase in the gas flow rate produces higher liquid velocities, especially for the liquid being in contact with or in the vicinity of the plume region. Overall liquid velocities increase as the gas flow rate increases. For a gas flow rate of $1.66 \times 10^{-2} \text{m}^3/\text{s}$ a maximum liquid velocity of 0.8 m/s is obtained at the exit of the nozzle, while at the same location a liquid velocity of 4 m/s is obtained when the gas flow rate is $1.5 \times 10^{-3} \text{m}^3/\text{s}$ (one order of magnitude higher). However, it should be noted that an extremely high value of 4 m/s is predicted at the nozzle location, where the gas volume fraction is around 97% (almost no liquid present at that point).

Figure 14 shows the temperature fields produced when the gas flow rates are varied from $1.66 \times 10^{-2} \text{m}^3/\text{s}$ to $1.5 \times 10^{-3} \text{m}^3/\text{s}$. Two main findings can be noted from this figure. The first is that the maximum temperature in the arc attachment zone increases as the gas flow rate increases, which represents a surprising result, since as the mixing increases due to gas injection one would expect lower temperature gradients. Maximum temperatures range from 1966 to 1999 K corresponding from the lowest to the highest gas flow rates. The second important observation is that the well-homogenized region expands to a bigger portion of the reactor as the gas flow rate increases. Then, despite the fact that the arc attachment zone is hotter as the gas flow rate increases most part of the reactor is better homogenized. Hence, combining these two main findings, it can be said that as the gas flow rate increases, the region dominated by electromagnetic forces is reduced to a smaller portion but this promotes a hotter arc attachment zone. This is mainly because there is no chance to dissipate the heat coming from the arc due to the reduce zone where electromagnetic stirring is dominating. Therefore, gas injection is beneficial (homogenizing temperature and species in the reactor), but care must be taken to avoid the formation of excessively hot regions. These hot spots (or the isolated region where the electromagnetic effects dominate) will lead to a poor dissipation of the heat coming from the arc, being the dissipation of the heat one of the most important objectives of the gas injection.
5. Conclusions

A mathematical model has been developed to represent DC-EAF refining operations. The model involves the simultaneous solution of Maxwell’s equations for the electromagnetic field, and the turbulent fluid flow and heat transfer equations. In solving the bath region it was assumed that the arc-bath interactions are dominated by the behavior of the arc. In contrast to previous modeling investigations, this work relaxes some critical assumptions and provides a more realistic and comprehensive representation of the system. Furthermore, due allowance was made to represent and analyze the effect of gas injection, the presence of a slag layer in the bath and the differences in anode configurations. Finally, a detailed analysis was carried out to examine the effect of process parameters (e.g., arc current, arc length, bath dimensions, anode arrangements, etc.) on the behavior of the furnace (i.e., heat transfer to the bath, heating efficiency, mixing in the bath, etc.). The main conclusions obtained from the bath model are the following:

(1) Fluid flow patterns, heat transfer and mixing characteristics were analyzed for a DC-EAF system with a radius of 1.5 m, liquid depth of 0.5 m, and constant wall temperatures at 1773 K operating under arc lengths and arc currents ranging from 0.15 to 0.35 m and 36 to 50 kA, respectively. Results of the model illustrate that, in the absence of inert gas stirring and with no slag present in the system, electromagnetic forces dominate and are responsible for a single, clockwise, circulation loop in the bath, with high velocities in the central region (downward flow) and relatively low velocities in the vicinity of the lateral wall (upward flow). Buoyancy and shear stress effects partially counteract the electromagnetic driven flow. The arc also controls temperature stratification in the bath. In fact, the largest gradients of almost all bath variables are located just below the arc, in the region called the “arc attachment zone”. Outside this zone a more uniform region is found.

(2) The effect of stirring by inert gas injection, considered in isolation, was analyzed in this study for gas flow rates ranging from $1.66 \times 10^{-4}$ to $1.5 \times 10^{-3}$ m$^3$/s with a three-nozzle injection system and the same arc characteristics and furnace dimensions stated above. The results indicate that sufficient mixing can be promoted in the periphery of the bath to prevent temperature stratification in that region, and to help dissipate the heat being supplied by the arc in the central region of the bath. Gas injection increases mixing in the bath and the larger the gas flow rate, the larger the mixing observed. The combination of gas injection and electromagnetic body forces can effectively eliminate dead zones in the reactor.

(3) Under the same arc characteristics and furnace dimensions, it can be stated that the effect of a slag cover is to reduce the velocity in the bulk of the bath, away from the arc region, and to raise the average bath temperature.

(4) An increase in arc length (in the range of 0.15 to 0.35 m) increases asymptotically the amount of energy introduced into the bath, and poorer mixed baths are obtained in a DC-EAF with furnace radius of 1.5 m, liquid depth of 0.5 m, and wall temperatures at 1773 K.

(5) An increase in arc current (in the range from 36 to 50 kA) increases linearly the amount of energy introduced into the melt and also improves mixing in a DC-EAF with radius of 1.5 m and liquid depth of 0.5 m.

(6) By changing the furnace radius from 1.5 to 2.5 m and the liquid depth from 0.35 to 0.7 m, over the range of arc characteristics employed in this study, it was found that the higher the furnace aspect ratio ($H/R_{furnace}$) the better for the mixing behavior in the melt and the energy optimization from the arc.

(7) Finally, under the range of arc characteristics and furnace dimensions analyzed in this study, the anode configuration can be changed to promote completely different flow patterns, which can be optimized to prevent refractory wear.

The model will also be potentially useful to address the study of other important issues in EAF operation, such as the position at which additions (for example ferroalloys) are more rapidly mixed and better recovered. Also, the locations for addition of DRI can be optimized to increase its dissolution rate.

Although further efforts are required in order to validate the model under actual steelmaking conditions, the authors feel that the bath model presented in this work can be used as a useful tool for gaining process understanding of DC-EAF operations.

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