Thermo-hydrodynamic simulation of a problem in steel industry - Nº23

P. Barral[1,2], L.J. Pérez-Pérez[1] and P. Quintela[1,2]

[1]Departamento de Matemática Aplicada, Universidade de Santiago de Compostela. Email: patricia.barral@usc.es, luisjavier.perez.perez@usc.es, peregrina.quintela@usc.es
[2]Technological Institute for Industrial Mathematics (ITMATI). Email: peregrina.quintela@itmati.com

Introduction

In steel industry it is of vital importance to minimize the wear that refractory linings suffer during several stages of the basic oxygen steelmaking process. The process starts at the blast furnace, where slag and hot metal are produced and subsequently poured onto the blast furnace runner, a trench-like structure composed of different layers of concrete refractories. The runner is designed to enable the separation of slag and hot metal due to their density difference.

Figure: Blast furnace runner schematic diagram.

The wear suffered by the refractories is due to a combination of factors, mainly corrosion and erosion, with thermal stresses also playing a role. It is also believed to be strongly related to the position of the so-called critical isotherms, which indicate the onset of chemical composition changes in the refractories.
A 3D mathematical model is proposed and solved on a computational domain imitating a runner used by the Arcelor-Mittal company in Veriña, Asturias, with the main purpose of finding the position of these critical isotherms.

Physical problem and computational domain

- The three involved fluid phases –air,slag and hot metal– are separated by free surfaces whose position is *a priori* unknown.
- A forced air flow circulates above the slag due to the aspiration performed next to the taphole, which enhances cooling by convection on the exposed parts of the runner and the slag free surface. The outermost part of the runner is refrigerated by the surrounding air, which circulates freely around the casthouse.
- The extremely high temperatures of slag and hot metal, around 1500°C, mean that radiation emission from the slag free surface is extremely relevant in heat transfer. A refractory cover structure prevents this thermal radiation from escaping to the surroundings, avoiding excessive cooling of the slag.

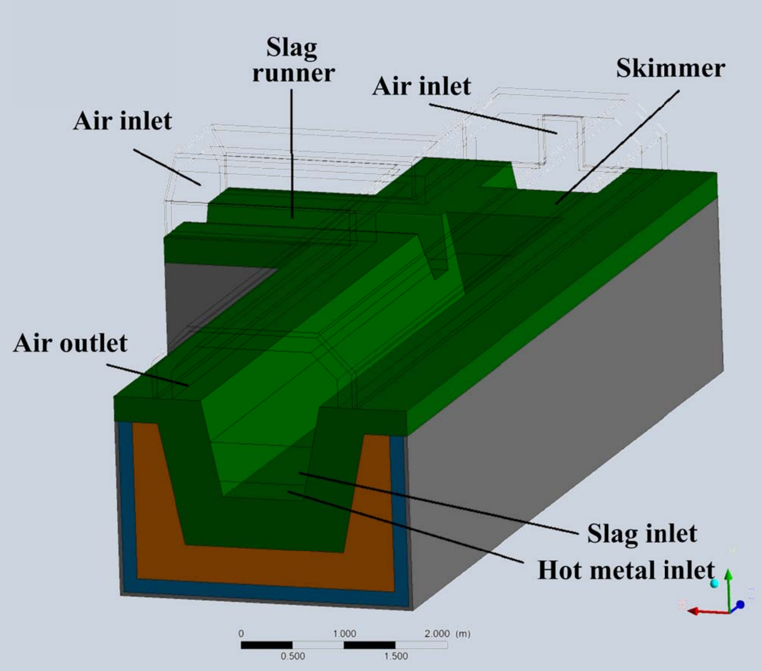

Figure: View of the computational domain.

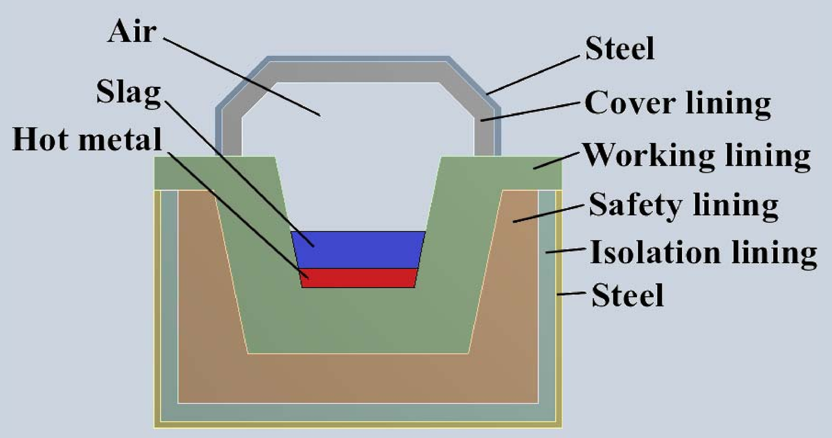

Figure: Tranversal cut of the runner.

- The computational domain Ω corresponds to the latter half of the runner, where slag and hot metal can be assumed to be well separated. We split it in a fluid subdomain Ω_f and a solid subdomain Ω_s.
- Constant properties are considered for both fluid and solid materials. Thus, the flow is assumed to be incompressible and the thermal model is decoupled from the hydrodynamic one.
- In spite of the casting process being discontinuous, with operation cycles having stops inbetween, both measurements and numerical simulations evidence that the temperature in the bulk of the solids slowly reaches a steady state. Thus, a steady state thermal model is used to find the position of the critical isotherms.

Hydrodynamic model

To model the different phases of the flow, the *Volume of fluid method* (VOF) is used. The fluid phases are considered as a single fluid occupying a fixed domain, with properties described using piecewise constant functions. A characteristic function φ, indicating if phase i is present at each $(\mathbf{x}, t)$, is approximated using the so-called *volume fraction* α_i:

$$\alpha_i = \frac{1}{\mathrm{Vol}(V)} \int_V \varphi_i dV, \tag{1}$$

where $\mathrm{Vol}(V)$ is the volume of the cell V. The properties of the fluids are taken as *mixture properties*. Hence, any scalar spatial field associated with an arbitrary property ϕ for phase i is taken as:

$$\tilde{\phi} = \sum_{i=1}^{N} \phi_i \alpha_i, \tag{2}$$

where N is the number of fluid phases involved.

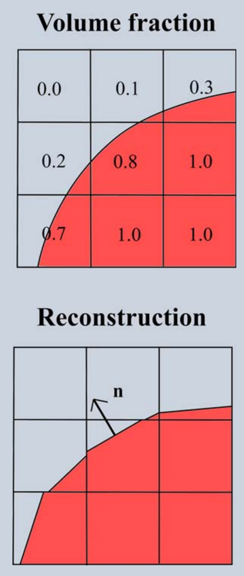

Figure: Free surface reconstruction.

The SST $K-\omega$ turbulence model is used to model the effect of the turbulence-related phenomena on the mean flow. The following equations are solved in Ω_f:

$$\begin{aligned}
&\mathrm{div}(\mathbf{V}) = 0,\\
&\frac{\partial \alpha_i}{\partial t} + \mathrm{div}(\alpha_i \mathbf{V}) = 0,\\
&\frac{\partial (\tilde{\rho}\mathbf{V})}{\partial t} + \mathrm{div}(\tilde{\rho}\mathbf{V}\otimes\mathbf{V}) = -\mathrm{grad}(\Pi) + \mathrm{div}\left(2(\tilde{\mu}_T + \tilde{\mu})D(\mathbf{V}) - \frac{2}{3}\tilde{\rho}K\mathbf{I}\right) - \tilde{\rho}g\mathbf{e}_3,\\
&\frac{\partial (\tilde{\rho}K)}{\partial t} + \mathrm{div}(\tilde{\rho}K\mathbf{V}) = \mathrm{div}\left[\left(\tilde{\mu} + \frac{\tilde{\mu}_T}{\sigma_K}\right)\mathrm{grad}\,(K)\right] + G_K - Y_K,\\
&\frac{\partial (\tilde{\rho}\omega)}{\partial t} + \mathrm{div}(\tilde{\rho}\omega\mathbf{V}) = \mathrm{div}\left[\left(\tilde{\mu} + \frac{\tilde{\mu}_T}{\sigma_\omega}\right)\mathrm{grad}(\omega)\right] + G_\omega - Y_\omega + D_\omega.
\end{aligned} \tag{3}$$

We denote as Π and $\mathbf{V}$ the mean fields of the pressure and velocity, whereas $D(\mathbf{V})$ denotes the symmetric part of the mean velocity gradient. With μ and ρ we denote the viscosity and density. In addition, μ_t is the eddy viscosity, computed using the specific dissipation rate ω and the turbulent kinetic energy K.

Boundary conditions: Fixed velocities are set at the fluid inlets whereas atmospheric pressure values are set for the outlets. The hot metal and slag velocities are extrapolated from daily production values and are equal to $\mathbf{V}\cdot\mathbf{n} = 0.074$ m/s and $\mathbf{V}\cdot\mathbf{n} = 0.035$ m/s, respectively. In addition, air is assumed to enter the domain through both inlets at $\mathbf{V}\cdot\mathbf{n} = 2$ m/s. At the solid walls, no slip is assumed.

Acknowledgements

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Thermal model

In $\Omega_f \cup \Omega_s$, the following equations are solved to obtain the temperature θ:

$$\begin{aligned}
&\mathrm{div}(\tilde{\rho}\tilde{c}_p\mathbf{V}\theta) = \mathrm{div}((\tilde{k} + \tilde{k}_T)\mathrm{grad}(\theta)), && \text{in } \Omega_f,\\
&\mathrm{div}(k\,\mathrm{grad}(\theta)) = 0, && \text{in } \Omega_s,
\end{aligned} \tag{4}$$

At the interfaces between fluids and solids, continuity of both temperature and heat flux $\mathbf{q} = \tilde{k}\mathrm{grad}(\theta)$ has to be satisfied. This is true except for $\delta\Omega_{f,a}$, where a radiation contribution Q_{rad} to the heat flux is applied. Consequently, we assume that:

$$[\mathbf{q}]_{\partial\Omega_{f,a}}(\mathbf{x}) \cdot \mathbf{n}_{f,a} = Q_{rad}(\mathbf{x}), \qquad \text{on } \delta\Omega_{f,a}. \tag{5}$$

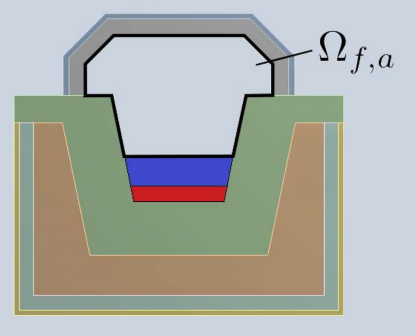

Figure: Radiation enclosure.

Boundary conditions: On the external walls of the runner, we set *convective* boundary conditions, also accounting for cooling due to radiation emission:

$$-k\frac{\partial\theta}{\partial \mathbf{n}} = h(\theta - \theta_{ext}) + \sigma\varepsilon(\theta^4 - \theta^4_{ext,r}), \tag{6}$$

with h being the convection coefficients and $\theta_{ext} = \theta_{ext,r} = 293$ K (20 °C) the external temperature. The value of these coefficients is estimated using empirical correlations for free convection.
On the inlets, we set that $\theta = 1500$ °C for hot metal and $\theta = 20$ °C in the case of air. For slag, we use a profile which varies from 1327 °C at the free surface with air to 1500 °C at the free surface with hot metal.

Radiation submodel

To compute Q_{rad}, the S2S radiation model is used. Slag and hot metal are opaque to radiation, as are all the solids. The boundary $\partial\Omega_{f,a}$, is divided in M open sets S_i.For each i, S_i is assumed to be a gray, diffuse, opaque surface, characterized by a constant temperature. The net radiation heat exchange between surfaces i and j verifies:

$$J_i = E_i + (1 - \varepsilon_i)\sum_{j=1}^{M} F_{ij}J_j, \tag{7}$$

where $E_i = \sigma\varepsilon_i\theta_i^4$ and J_i is the radiosity, which is the outgoing radiation flux from surface i. The *view factors* F_{ij} represent the fraction of outgoing radiation radiation from surface i intercepted by surface j:

$$F_{ij} = \frac{1}{A_i}\int_{A_i}\int_{A_j} \frac{\cos\psi_i \cos\psi_j}{\pi R^2}\delta_{ij}\, dA_j dA_i, \tag{8}$$

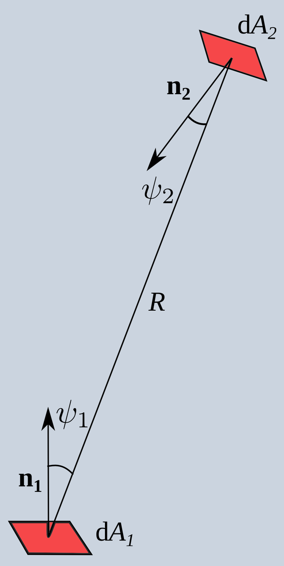

Figure: View factor.

Emissivity ε has to be supplied in all the surfaces composing $\delta\Omega_{f,a}$. Measured values are used in the refractories and slag. At the air inlets it was set that $\varepsilon = 1$ and $\theta = 293$ K whereas at the outlet $\varepsilon = 0$ is used. As the temperature at each surface is known, equations (7) for all $i \in \{1, \ldots, M\}$ can be regarded as a linear system of M equations and unknowns. Its solution yields the value of the radiosity, which is used to calculate the net heat flux due to radiation:

$$q_{rad,i} = J_i - \sum_{j=1}^{M} F_{ij}J_j. \tag{9}$$

Then, the $Q_{rad}(\mathbf{x})$ term, needed to compute the jump of the heat flux in (5), is obtained as a piecewise constant function $Q_{rad}(\mathbf{x}) = q_{rad,i}$, if $\mathbf{x} \in S_i$.

Results

- The solution procedure is as follows: first, the transient hydrodynamic model is solved until a quasi-steady state is reached, which means that the computed position of all the free surfaces is stationary. Then, those surfaces corresponding to slag-air and hot metal-air are reconstructed as walls and the steady state thermal model is solved.
- The models are solved using ANSYS Fluent on a grid composed of 21 million cells.
- With the given boundary conditions, the free surfaces are found to be almost completely plane.

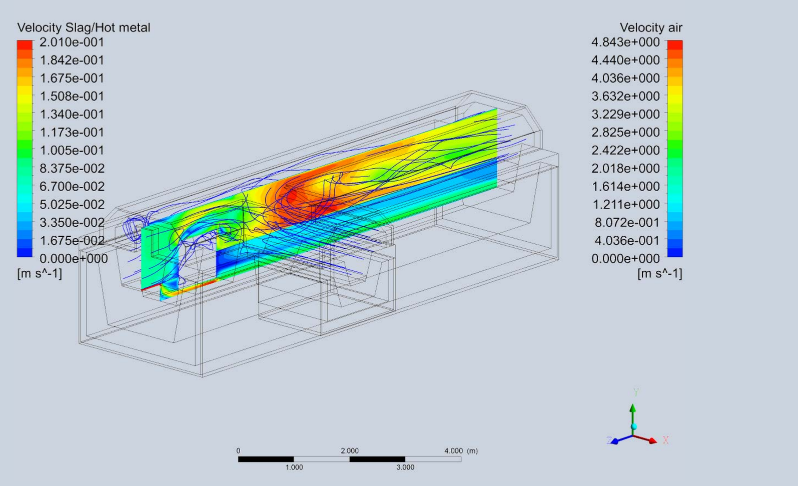

Figure: Velocity modulus and streamlines in the air phase.

- Temperatures in the slag free surface drop rapidly as it flows downstream, suggesting that solidification may take place. Conversely, hot metal remains at approximately the same temperature as it flows out of the domain.
- Both isotherms (1200°C and 1250°C) are located inside the working lining, even though the 1200°C one is close to the safety lining in the central part of the runner. This indicates that themal damage is sustained mainly by the working lining.

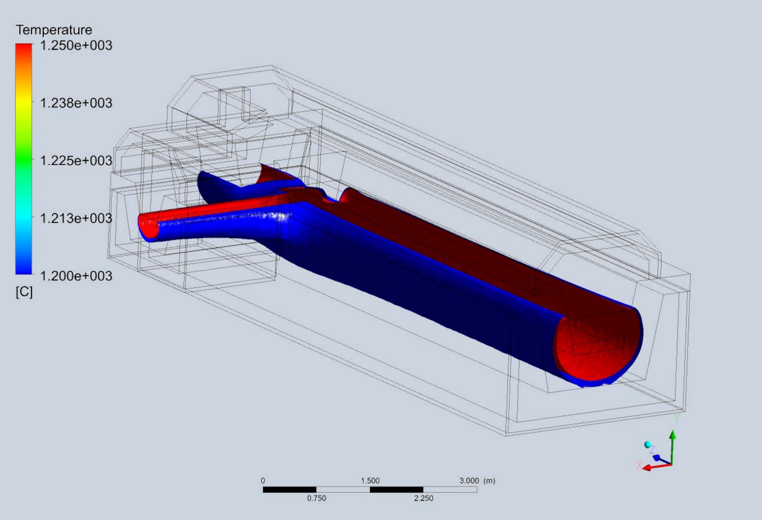

Figure: Position of the critical isotherms.

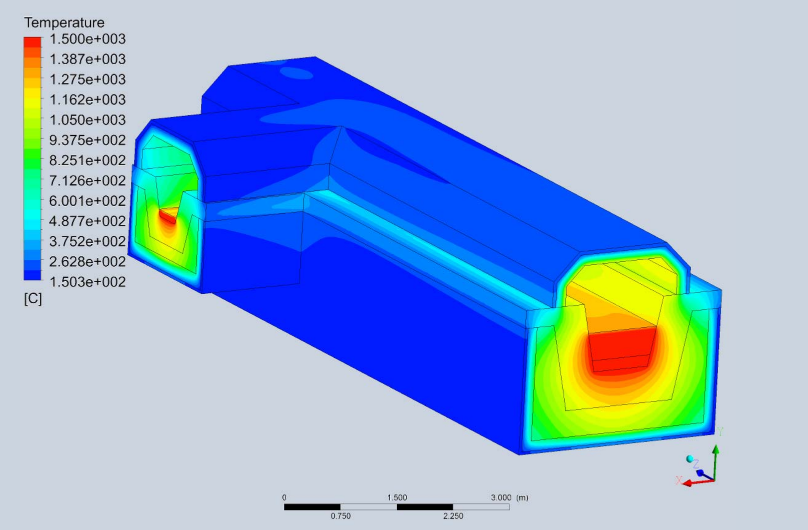

Figure: Temperature field in the runner.

Validation

ArcelorMittal has provided temperature measurements obtained using six thermocouples embedded inside the insulation lining. Good agreement is obtained, even though the test is not very significant due to the suboptimal thermocouple placement, far away from the position of the critical isotherms.

	Measured	Numerical	Absolute error	Relative error
TC1	576	596.2	20.2	$3.5\cdot10^{-2}$
TC2	669	617.9	51.1	$7.6\cdot10^{-2}$
TC3	755	767.4	12.4	$1.6\cdot10^{-2}$
TC4	770	759.1	10.9	$1.4\cdot10^{-2}$
TC5	644	645.8	1.8	$2.8\cdot10^{-3}$
TC6	626	625.8	0.2	$3.2\cdot10^{-4}$

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