# HOT METAL FLOW IN THE BLAST FURNACE HEARTH: THERMAL AND CARBON DISSOLUTION EFFECTS ON BUOYANCY, FLOW AND REFRACTORY WEAR

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# ABSTRACT

The lower part of an iron making blast furnace, *the hearth*, consists of a packed bed of coke particles through which liquid hot metal flows during tapping. During tapping, complicated processes take place in which e.g. carbon is transferred from the coke to the liquid iron and wall cooling cools the hot metal. In 2D CFD calculations (3D is not yet implemented), with simple geometries, the effects on density changes of the hot metal due to cooling (higher hot metal density) and carbon dissolution (lower hot metal density) is studied. The effects on hot metal flow due to buoyancy are shown and the effects of fluid speed on carbon dissolution rate are shown. Since carbon dissolution from refractory bricks is similar compared to carbon dissolution from cokes, refractory wear is evaluated by analysing fluid flow along the wall.

2D results show remarkable zones with high carbon concentration, low fluid speed and thus high retention (residence) time. Stratification occurs, separating the hearth in two zones: high fluid speed zone and low fluid speed zone. Hot metal circulation in the low fluid speed zone causes a separation in the lower zone: a high and low carbon concentration zone. High fluid speed zones along the wall occur directly opposite to the tap hole and around the tap hole. Consequently these areas show high carbon dissolution rates.

KEYWORDS: blast furnace, carbon dissolution, buoyancy, CFD, refractory wear.

# NOMENCLATURE

$A_C$	interface area coke/liquid	
$C_i$	composition	
$D_{C-Fe}$	<i>Fe</i> diffusivity of carbon into (liquid) i	
g	gravitational acceleration	
$h_{tot}$	specific total enthalpy	
$k_0$	reaction rate constant	
$K, K_C, K_R$	reaction (dissolution) rate constant	
р	pressure	
R	resistance to (porous) flow	
$r_C$	carbon atom radius	
$S_E$	energy source	
SM	momentum source, body force	
$S_V$	viscous energy source	
Т	temperature	
$T_m$	melting temperature of iron	
u	velocity	
<b>u</b> <sub>0</sub>	reference velocity (usually=1)	
$V_m$	melt volume	

$Y_C$	mass fraction carbon in hot metal
$Y_{CS}$	mass fraction carbon in carbon-saturated hot
$Y_{OC}$	reference mass fraction carbon in hot metal
	(usually= 0)
$\alpha_{c}$	coefficient of expansion
β	coefficient of thermal expansion
ε ( <b>ε</b> )	volume porosity (tensor)
ĸ	Boltzmann's constant
λ	thermal conductivity
μ	dynamic viscosity
0	density

 $\rho_0$  reference density (at  $T_m$ )

$\nabla$	gradient

- $\nabla$  divergence
- ⊗ tensor product

# INTRODUCTION

Basically, the blast furnace is a counter current heat and mass exchanger in which rising reduction gas loses most of its heat on the way up, leaving the furnace at a temperature of about 200° C, while descending iron oxides are wholly converted to metallic iron (Walker, 2000).

In the upper part of the blast furnace (see **Figure 1**), evenly sized sinter, coke and pellets are charged. The charge descends regularly, without sticking, because the narrow range of particle sizes makes the gas flow evenly, enhancing contact with the descending solids. While descending, the iron bearing part of the burden reacts with the rising reduction gases. It is heated and the iron oxides are (partially) reduced. When the temperature is high enough the iron (oxides) starts to soften and eventually melts. The melt (iron and slag) and the remaining coke collect in the lower part of the blast furnace: *the hearth*. The remaining coke forms a porous bed: *the dead man*. By drilling a tap hole below melt level, the hearth is emptied continuously (by regularly opening another tap hole). The liquid hot metal is tapped into a torpedo ladle.



Figure 1: Artist impression of a cross-section of a blast furnace.

The transport phenomena and physical status in the hearth of an iron making blast furnace are very complicated and difficult to monitor and characterise. The non-uniform flow, heat transfer, and carbon dissolution from the refractory and the coke bed (dead man) cause large differences in thermal conditions and hot metal composition. It is a challenging and a demanding task to relate available measured data with basic phenomena inside the hearth.

To incorporate the effects of distributed properties of the coke, like particle size distribution, a population balance model is set up to describe the effects of carbon dissolution from the cokes bed on particle size distribution, local porosity and local hot metal composition (Post *et al.*, 2002; Post *et al.*, 2003). Using CFD as a modelling tool, a hybrid numerical model has been constructed which incorporates the dissolution model, to study hot metal flow in 2D and 3D geometries of the hearth of a blast furnace.

This paper discusses the results of case studies (2D only) on the influence of hot metal density changes<sup>1</sup>, either thermally driven and/or caused by carbon dissolution, on the flow behaviour of hot metal during a tap. By analysing the fluid speed along the refractory walls an indication of the refractory wear rate is given.

### MODEL DESCRIPTION

### General description

# Simple 2D geometry

To study the effects of density changes on fluid flow through a porous medium, a simple rectangular 2D geometry was defined within the CFD code. The size of the model approximated the size of an actual large blast furnace (approx. 14 m in diameter). Liquid iron and a porous volume with the properties of a packed coke bed (porosity, thermal conductivity) were defined. The carbon dissolution model was defined in a separate user routine.



Y I Z

Figure 2: Porous volume in the 2D geometry. Blue and red lines denote entrance and exit respectively. Note the area around the exit with porosity = 1.0, to avoid excessive pressure drop at the exit.

#### Heat losses

In the blast furnace the wall and refractory of the hearth are cooled. Defining a heat flux across the sidewall and the bottom of the 2D geometry simulates wall cooling. The effect will be a temperature gradient across the hearth and thus a thermally driven density gradient across the hearth.

### Carbon dissolution (coke)

Several researchers have investigated the dissolution of carbon (from coke) into hot metal (Kosake *et al.*, 1968; Gudenau *et al.*, 1990; Jones, 1998). Gudenau *et al.* (1990) presented a relationship between carbon dissolution and the melt speed, based on experiments with rotating coke cylinders in a hot metal bath.

$$\frac{\partial Y_C}{\partial t} = K_C \frac{A_C}{V_m} \left( Y_{CS} - Y_C \right) \tag{1}$$

$$K_{C,0} = k_0 \left(\frac{u}{u_0}\right)^{0.7}$$
(2)

 $K_{C,0}$  is in m/s.

$$K_{C} = K_{C,0} e^{-K_{C,0} \frac{A_{C}}{V_{m}}t}$$
(3)

From Jones (1998):

$$Y_{CS}(T) = \frac{1.35 + 2.54 \cdot 10^{-3}T}{100}$$
(4)

*T* is in degrees Celsius ( $^{\circ}$ C).

### Carbon dissolution (refractory)

Gudenau *et al.* (1991) did similar carbon dissolution experiments with refractory bricks like the experiments with cokes. They concluded that an analogous relation could be established for the dissolution of carbon from refractory bricks (containing carbon). Preuer *et al.* (1993) used their findings in a CFD model to compute the combined effects of carbon dissolution from the coke bed and the refractory wall:

$$\frac{\partial Y_c}{\partial t} = K \cdot \left( Y_{cs} - Y_c \right) \tag{5}$$

$$\frac{1}{K} = \frac{1}{K_c} + \frac{1}{K_R} \tag{6}$$

<sup>&</sup>lt;sup>1</sup> No changes in packed cokes bed properties, like local porosity or particle size distribution, are considered.

 $K_R$  (in *m/s*) is the Arrhenius-like carbon dissolution rate constant for refractory bricks (*cf.*  $K_C$ ).

Carbon dissolution from the refractory is at this stage not yet implemented in the model discussed in this paper. Refractory wear rate is evaluated by considering the fluid flow speed at the refractory walls.

## Simple 3D geometry

Figure 3 shows the geometry that is used for setting up the 3D CFD model.



**Figure 3:** Typical blast furnace internal hearth 3D geometry (no refractory visible).

As with the 2D-model, the "size" and shape of the 3Dmodel is modelled according to a "real life" blast furnace. The number of grids is large due to the choice of a maximum node distance of 0.5 metres. Accordingly convergence takes a lot of time and 3D case studies are not done yet. The complete model physics (population balance, carbon dissolution, particle size distribution) is already implemented. Case studies will be done within the month.

### **Governing equations**

Using CFD software (CFX<sup>®</sup> 4.4 from AEA technology) the general Navier-Stokes equations of conservation for mass and momentum are numerically solved. The results are the basis for examining fluid flow behaviour in the flow simulations.

Equations for continuity (steady state):

$$\nabla \cdot (\rho \mathbf{u}) = 0 \tag{7}$$

Equations for momentum:

$$\nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) = \nabla \cdot \boldsymbol{\sigma} + \mathbf{S}_{\mathbf{M}} \tag{8}$$

The stress tensor  $\sigma$ :

$$\boldsymbol{\sigma} = -p\boldsymbol{\delta} + \boldsymbol{\mu} \Big( \nabla \mathbf{u} + (\nabla \mathbf{u})^T \Big)$$
(9)

Equation for energy (steady state):

$$\nabla \cdot (\rho \mathbf{u} h_{tot}) = \nabla \cdot (\lambda \nabla T) + S_V + S_E \tag{10}$$

The specific total enthalpy  $h_{tot}$  is defined as:

$$h_{tot} = h + \frac{1}{2}u^2 \tag{11}$$

The viscous shear effect (source)  $S_v$  is:

$$S_{V} = \nabla \cdot \left( \mu \left( \nabla \mathbf{u} + \left( \nabla \mathbf{u} \right)^{T} - \frac{2}{3} \nabla \cdot \mathbf{u} \delta \right) \mathbf{u} \right)$$
(12)

# **Buoyancy and Flow Through a Porous Medium**

In equation (8) the momentum source  $S_M$  is a body force. The CFD model is simulating fluid flow through a porous medium (the dead man), where in addition the density of the fluid changes as a function of temperature and composition. The body force becomes then

- Buoyancy force,  $\mathbf{S}_{\mathbf{M}} = \rho \mathbf{g}$  and  $\rho = \rho(T, C_i)$
- Resistance force in flow through porous media,  $\mathbf{S}_{\mathbf{M}} = -\mathbf{R} \cdot \mathbf{u}$

The combination of both forces is:

$$\mathbf{S}_{\mathbf{M}} = \rho \mathbf{g} - \mathbf{R} \cdot \mathbf{u} \tag{13}$$

The density in the buoyancy force term  $\rho \mathbf{g}$ , can be rewritten to:

$$\rho = \rho_0 + \left(\rho - \rho_0\right) \tag{14}$$

For low fluid velocities and small temperature differences, the Boussinesq approximation for estimating buoyancy forces, suffices:

$$\rho = \text{constant} = \rho_0 \tag{15}$$

In addition to the buoyancy terms in the momentum equations where:

$$\rho = \rho_0 \Big[ 1 - \beta \big( T - T_0 \big) \Big] \tag{16}$$

the effect of additional mass (carbon) on density due to carbon dissolution is also present:

$$\rho = \rho_0 \Big[ 1 + \alpha_C \big( Y_C - Y_{0C} \big) \Big] \tag{17}$$

Combining both effects will give:

$$\rho = \rho_0 \left( 1 + \left[ \alpha_C \left( Y_C - Y_{0C} \right) - \beta \left( T - T_m \right) \right] \right)$$
(18)

For porous flow the following general equations for mass and momentum hold (steady state):

$$\nabla \cdot (\rho \mathbf{\epsilon} \cdot \mathbf{u}) = 0 \tag{19}$$

$$\nabla \cdot \left( \rho(\boldsymbol{\varepsilon} \cdot \mathbf{u}) \otimes \mathbf{u} \right) - \nabla \cdot \left( \mu \boldsymbol{\varepsilon} \cdot \left( \nabla \mathbf{u} + \left( \nabla \mathbf{u} \right)^T \right) \right)$$
  
=  $-\boldsymbol{\varepsilon} \mathbf{R} \cdot \mathbf{u} - \boldsymbol{\varepsilon} \nabla p$  (20)

#### Temperature dependence of physical properties

#### Hot metal density

Liquid iron density changes as a function of temperature. A temperature dependent expression is available in several publications (Jones, 1998; Brandes *et al.*, 1998)

$$\rho = \rho_0 + \left[ -0.883 \cdot 10^{-3} \cdot \left( T - T_m \right) \right]$$
(21)

 $\rho$  is in kg  $m^{-3}$ .

#### Hot metal viscosity

Like hot metal density, hot metal viscosity is also temperature dependent (Brandes *et al.*, 1998)

$$\mu = 0.3699 \cdot 10^{-3} e^{\frac{41.4 \cdot 10^{\circ}}{R \cdot (T + 273.15)}}$$
(22)

 $\mu$  in kg·m·s<sup>-1</sup>, R is the gas constant (8.314 J·mole<sup>-1</sup>·K<sup>-1</sup>) and T is in degrees Celsius (°C).

### Carbon diffusivity

Kosake *et al.* (1968) determined that carbon diffusivity in liquid iron was approximated best by Li-Chang's formula

$$D_{C-Fe} = \kappa \cdot \frac{(T+273.15)}{8\mu r_c} \tag{23}$$

 $D_{C-Fe}$  is in  $m^2 \cdot s^{-1}$ , *T* is in degrees Celsius (°C),  $\kappa$  is Boltzmann's constant (1.3807 $\cdot 10^{-23} J \cdot K^{-1}$ ) and  $r_C$  is the radius of the carbon atom (*m*).

### Coding and input data of the model

The 2D and 3D geometries were setup in CFX<sup>®</sup> 4.4, the dissolution model (only carbon dissolution) was coded in MATLAB. A FORTRAN and C/C++ interface was coded to implement the MATLAB routine (in C/C++) in CFX<sup>®</sup>. Since MATLAB<sup>®</sup> handles matrices and arrays in general more efficient than FORTRAN, all matrices and array operations necessary to execute the dissolution model calculations and data transfer, were handled by the MATLAB routines.

Input data/Boundary conditions/Geometry data			
Carbon in hot metal entering hearth, Chew <i>et al.</i> (2001)	0 – 2.5 wt%		
Temperature at inlet	1600 °C		
Density at $T_m$	7015 kg⋅m <sup>-3</sup>		
Fluid speed at liquid level	$0.0003 \text{ m}\cdot\text{s}^{-1}$		
Pressure at liquid level	4 bar		
Coke bed volume porosity	0.35		
Grid (2D)	60x30 cells		

# **RESULTS AND DISCUSSION**

### Isothermal case (2D)

In **Figure 4** and **Figure 5** case study results of the isothermal case are presented. Smooth flowing streamlines indicate neither recirculation patterns, nor any areas where residence time differs greatly from other areas. As expected, the highest velocities are near and in the exit

area (result of boundary conditions: fluid speed at entrance is constant). The isothermal results presented here, mainly serve to illustrate the differences between the other cases.

### Non-isothermal case, without carbon dissolution (2D)

**Figure 6, Figure 7** and **Figure 8** show the results for the case study of hot metal flow through a non-reactive porous bed, while the walls are being cooled.

A clear stratification occurs: a high (fluid) speed zone and a low-speed zone. In the high-speed zone, the residence time is no more than 2 hours; while in the low-speed zone residence time of more than 8 hours occur. Hot metal exchange takes place by cooled down hot metal (at the wall), which flows along the wall to the low-speed zone. The stratification is caused by density differences, caused by the temperature gradient across the hearth.

### Non-isothermal case, with carbon dissolution (2D)

Figure 9 to Figure 12 show the results of case studies where hot metal flows through a reacting (dissolving) porous coke bed. Competing effects of carbon dissolution into the hot metal and cooling of the hot metal (density effects), causes buoyancy effects. The main effect is stratification into two zones: a high- (fluid) speed and a low-speed zone (Figure 9). The streamline graph (Figure 12) shows the large differences in residence time. As a result the carbon dissolution rate graph (Figure 10) show high dissolution rates in the high-speed zone. Remarkable high dissolution rate zones occur: near and around the tap hole and straight across the tap hole at the other wall. Near the tap hole, the high dissolution rates are caused by the high exit speed of the fluid, below the tap hole and straight across the tap hole, the high dissolution rates are caused by (relatively) high speeds due to cooling of the hot metal.

Carbon is accumulating in the low speed zone, with a remarkable split into two regions in the low speed zone. This split is caused by an upward directed recirculation flow, which partly screens one region from relatively "fresh" (i.e. low in carbon concentration) hot metal.

Relatively large difficulties occur in reaching convergence in the calculations. The competing buoyancy effects of cooling and dissolution play havoc with reaching steady state results: the flow is intrinsically unsteady. Future work will focus on the unsteady and three-dimensional effects of this buoyancy phenomenon.



Figure 4: Velocity vector graph for the isothermal case.

# Time



[s] Y Figure 5: Streamlines for isothermal case (no dissolution). Colouring is based on residence time while "travelling" along a streamline.





[K]





Figure 7: Normalised velocity vector graph for the non-isothermal case (no dissolution).

# Time



Figure 8: Streamlines for non-isothermal case (no dissolution). Colouring is based on residence time while "travelling" along a streamline.



Figure 9: Non-isothermal case with carbon dissolution (2D).





Figure 10: Non-isothermal case with carbon dissolution, carbon dissolution rate.

#### Carbon Mass Fraction



Figure 11: Non-isothermal case with carbon dissolution, carbon concentration

#### Time



Figure 12: Streamline graph. Colouring is based on residence time while "travelling" along a streamline.

# CONCLUSIONS

Competing effects on buoyancy by carbon dissolution and cooling, create:

- Stratification: two major fluid speed zones.
- Recirculation in the low speed zone.
- High and low carbon concentration zones.
- High carbon dissolution rates at specific places: around and below the tap hole and straight across at the other wall.

Although the general furnace shape and exit shape (tap hole) of the 2D model does not resemble a real blast furnace hearth, the significance of the competing effects (for a real life 3D situation) can already be seen from the 2D simulation results.

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