# Simulation of Slag/Gas and Slag/Iron Interface Tilting in Blast Furnace Hearth during Slag Tapping

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## Introduction

Blast furnace is a type of counter current shaft furnace used for iron ore reduction and smelting to produce industrial liquid iron. In a blast furnace, coke, ores, and flux (gravel) are charged at the top of the furnace, while a hot blast of air (usually with pulverized coal and oxygen enrichment) is blown into the lower section of the furnace through a series of pipes called tuyeres. The chemical reactions take place throughout the furnace shaft as the burden material (layers of ore and coke) moves downward. The end products are molten iron and slag phases tapped from the bottom, and flue gases exit from the top of the furnace. The typical structure of a blast furnace is show in Figure 1. The focus of this study is the tapping process at the blast furnace hearth.

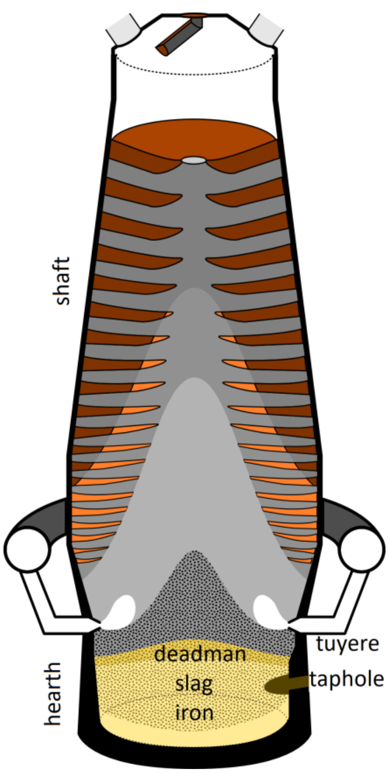


**Figure 1**. Overview of the blast furnace structure.

The blast furnace hearth drainage constitutes a major part of the blast furnace operation. Especially, keeping track of the iron and slag levels is crucial to adapt the right tapping strategy. The operational target is usually not only to empty the blast furnace as far as possible but also to keep the slag below a critical level to prevent flooding of the tuyeres where the hot blast is injected into the furnace. The tuyere flooding is a dangerous disturbance in blast furnace operation since it mostly leads to tuyere damages, which is a serious threat to safety. Therefore, characterizing the movements of the slag/gas and slag/iron interfaces during tapping is an important issue.

The blast furnace hearth is filled with a coke bed also called “deadman”, which supports the burden weight in the shaft and slowly dissolves in the molten iron. High quality coke is necessary for a well-performing deadman. Otherwise, the carbon concentration in the molten iron gets low, consequently, the carbon refractories of the hearth wall are dissolved in the liquid iron, which reduces wall thickness and thus shortens the campaign life time. A well-performing deadman also means good permeability and drainage characteristics.

The blast furnace tapping operation starts by drilling the taphole. The selection of taphole drill diameter is an important operational parameter which influences the tapping rate. Besides the tapping rate generally increases due to the taphole wear, in which taphole clay plays a key role. Subsequently, the iron and slag tapping rate controls the tilting of the slag/gas and slag/iron interfaces. Usually, the initial slag/iron interface is above the taphole level and first only iron comes out of the taphole. Since the iron viscosity is much lower, it is assumed that during the first period of tapping the iron/slag and slag/gas interfaces stay horizontal. Once the slag/iron interface level is equal to the taphole level, a mixture of iron and slag comes out of the taphole. Afterwards the interfaces stay no longer horizontal. The high viscosity of the slag causes the tilting of the interfaces. Therefore, the later mixed iron and slag tapping period constitutes the main focus of the simulation model.

The tilting effect depends on a variety of conditions, e.g. the permeability of the deadman, the viscosity and density of the slag phase, tapping rate, hearth size and taphole length. To simplify the model, as an initial approach, the deadman is assumed to be uniform and stationary. This assumption is partially a reasonable assumption since most of the modern large size blast furnaces are considered to have a so-called sitting deadman, which touches the hearth bottom and stays stationary, The main results of the model are the iron and slag levels during tapping and the remaining slag and iron mass in the hearth after tapping. Hence, it serves as a very useful tool for the analysis of the blast furnace tapping process in order to avoid tuyere flooding, which may lead to serious dangers and damages.

## Theory and Governing Equations

The computational fluid dynamics (CFD) simulations are computationally expensive to solve. Therefore, keeping the model as simple as possible without losing too much accuracy is a key issue. So a simplified approach has been considered by focusing on the slag flow instead of a complex multiphase flow model.

The molten slag has a much higher viscosity than the molten iron. Thus, practically only the flow of molten slag through the coke bed (deadman) is restricted and governs the interface tilting phenomena. This causes the tilting of the slag/gas interfaces during the later stage of tapping after slag arrival. The tilting of the slag/gas interface introduces non-uniform slag-weight distribution. This causes the tilting of the slag/iron interface. That means both slag/gas and slag/iron interface movements are only related to the slag. Hence, a single phase slag flow in porous bed with moving slag/gas interface at top and moving slag/iron interface at bottom has been formulated and implemented.

The flow through the deadman in the hearth is modelled using the Brinkman and Forchheimer equations in COMSOL Multiphysics®. The slag/gas and slag/iron interfaces are modeled using the moving mesh physics in COMSOL Multiphysics®. The sloshing tank example in Comsol Multiphysics' model library [1] is used as a template for the model development. At the beginning of the slag arrival at the taphole, it is assumed that the iron/slag and slag/gas interfaces are horizontal. The typical initial slag phase geometry is assumed to be a disk with hearth inner radius $R_h$ and thickness $H_s$ as shown in Figure 2. The deadman is assumed to be a uniform and stationary porous bed with porosity $\varepsilon_c$. The coke particles are assumed to have same spherical shapes with diameter $D_c$. The taphole entrance is shifted inwards by distance $L_m$ due to a built-up of taphole clay on the inner side of the refractory wall. The operational taphole drill length directly delivers this inward shift $L_m$. In the model, the slag leaves the hearth over a circular boundary around taphole entrance. Its diameter $D_{cf}$ represents the size of the coke filter in front of the taphole entrance region.

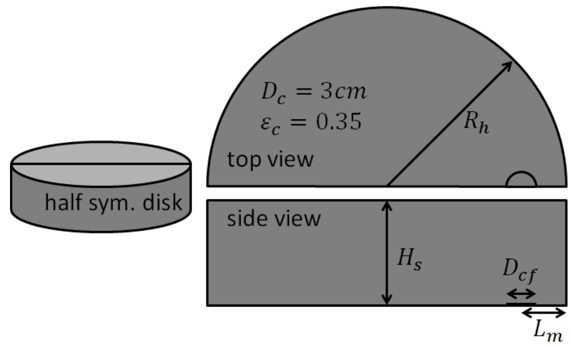


**Figure 2**. Initial geometry of the model.

**Slag flow in the deadman:**
The slag flow is modelled using the "Free and Porous Media Flow (fps)". Due to the high viscosity of the slag phase, the slag/gas interface does not stay horizontal during the slag tapping. The resulting non-uniform slag weight also tilts the slag/iron interface at bottom. These interface movements are explained in detail on the next sub-section of the paper. The complete domain for the slag flow is selected as a porous matrix. The permeability and Forchheimer drag terms are computed as given in the model library example for the Forchheimer flow [2]. The pressure drop in the coke bed (deadman) is modelled by the Brinkman equation such that the permeability $\kappa$ and the Forchheimer coefficients $\beta_F$ correspond to Ergun's equation:

$$\kappa = \frac{\varepsilon_c^3 \cdot D_c^2}{150(1-\varepsilon_c)^2}$$

$$\beta_F = 1.75\frac{(1-\varepsilon_c)\cdot\rho_s}{\varepsilon_c^2 \cdot D_c}$$

where, $\varepsilon_c$ is the coke bed porosity, $D_c$ is the equivalent coke particle diameter, and $\rho_s$ is the slag density. The typical values of the model parameters are given below:

| | |
|---|---|
| $D_c = 3$ cm | coke particle diameter |
| $\varepsilon_c = 0.35$ | deadman porosity |
| $\rho_i = 6700 \text{ kg/m}^3$ | molten iron density |
| $\rho_s = 2800 \text{ kg/m}^3$ | molten slag density |
| $\mu_i = 0.006 \text{ Pa} \cdot \text{s}$ | molten iron viscosity |
| $\mu_s = 0.435 \text{ Pa} \cdot \text{s}$ | molten slag viscosity |

Similar to the sloshing tank example [1], the slip condition is chosen for the vertical walls. The inlet boundary condition at the slag/gas interface is set as normal stress $f_0 = 0 \text{ N/m}^2$, which is the condition for an open boundary. The outlet boundary is set as laminar outflow with a flow rate $\dot{V}_s$, which is double as much as the slag production rate since the half of the geometry is simulated. As a remark to the reader, the discharge rate of the molten iron is directly modelled with the slag/iron interface movement.

**Slag/gas and iron/slag interface movements:**
The slag/gas and iron/slag interface movements are modelled using the "Moving Mesh (ale)". As already stated before, the sloshing tank example in Comsol multiphysics' model library [1] is used as a template. In order to follow the motion of the slag/gas and slag/iron interfaces with the moving mesh, it is necessary to (at least) couple the mesh motion to the fluid motion normal to the surface. It turns out that for this type of free surface motion, it is important to not couple the mesh motion to the fluid motion in the tangential direction. Otherwise, the mesh too soon becomes deformed and more often remeshing is required.

The boundary condition for the mesh equations on the hearth walls are set as prescribed mesh displacement using the global coordinate system $d_x = d_y = 0$ and $d_z = \text{free}$.

The boundary condition for the mesh equations on the slag/gas interface is set as prescribed mesh velocity using the boundary coordinate system $v_{t1} = v_{t2} = \text{free}$ and the velocity component in surface normal direction is:

$$v_n = \frac{n_x u + n_y v + n_z(w + w_{s0} + w_i)}{\varepsilon_c}$$

where, $\varepsilon_c$ is deadman porosity, $(n_x, n_y, n_z)$ are components of the unit surface normal, $(u, v, w)$ are velocity components of the slag flow in the porous bed, $w_{s0}$ is the average slag level increase due to slag production rate $\dot{V}_s$ is expressed by $w_{s0} = \frac{\dot{V}_s}{\pi R_h^2}$ and $w_i$ is the slag level decrease due to iron tapping and movement of slag/iron interface. This concept is developed during the RFCS project "SUSTAINTAP" in [3] by the authors.

The excess slag pressure occurs upon the tilting of the slag/gas interface due to the weight of the slag $\Delta h$. This causes the tilting of the slag/iron interface at the bottom (see Figure 3). The vertical velocity of the slag/iron interface $w_i$ is defined by the rate of iron volume change in the hearth scaled by the excess slag pressure:

$$w_i = -\dot{V}_i \cdot \frac{\Delta h}{2\int_S \Delta h \, dS}$$

where $\Delta h$ is the height of slag causing excess slag pressure. The fraction $\frac{\Delta h}{2\int_S \Delta h \, dS}$ defines the spatial distribution of level sink rate due to the decrease in the iron volume in the hearth. It is assumed that the iron tapping rate is double as much as the iron production rate $\dot{V}_i$ so that the net iron volume change rate is $-\dot{V}_i$.

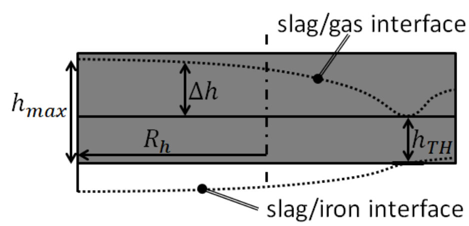


**Figure 3**. Slag/gas and slag/iron interfaces shown at vertical symmetry plane.

**Study settings and automatic remeshing:**
A time dependent study needs to be solved with automatic remeshing option. A typical tapping mostly finishes in less than one hour after the slag arrival. The automatic remeshing must be activated in order to avoid problems related to low mesh quality. The built-in variables in COMSOL's ALE feature can be comfortably used as general remeshing conditions:

$$\text{comp1.ale.I1isoMax} > 0.5 \quad \text{or}$$
$$\text{comp1.ale.minqual} < 0$$

Additionally, a stop condition is added to indicate the end of the tapping, i.e., the slag/gas interface reaches the taphole entrance. The model variable $h_{TH}$ in Figure 3 can be comfortably used in stop expression. Furthermore, the surface smoothness of the slag/gas interface just above taphole is also an indication to the end of the taping. Again, built-in spatial surface curvature variable can be comfortably used to detect so-called viscous fingering, which is a narrow bridge of gas penetrating towards the taphole entrance.

## Simulation Results

Keeping track of the iron and slag levels is crucial to adapt the tapping strategy (e.g. choice of drilling diameter and tapping times) in the hearth drainage process. The slag level should be always below the tuyeres to prevent flooding. Tuyere flooding leads to the most serious dangers and damages which may occur in the blast furnace operation. Therefore, characterizing the movements of the slag/gas and slag/iron interfaces during tapping is a critical issue. So the model is designed such that the main results are the iron and slag levels during the tapping as well as the remaining slag and iron mass in the hearth after the tapping, which are very useful for the analysis of the blast furnace tapping process in order to avoid dangerous tuyere flooding.

Figure 4 shows the maximum slag level $\boldsymbol{h_{max}}$, which occurs opposite to the taphole, and the min slag level $\boldsymbol{h_{TH}}$, which occurs at the taphole entrance. The sudden drop of the min slag level $\boldsymbol{h_{TH}}$ indicates the end of the tapping process when gas penetrates towards the taphole entrance. The slag/gas and slag/iron interface geometries at the end of a tapping cycle looks like Figure 5. A considerable amount of residual slag remains in the hearth inevitably. Due to the high viscosity of the slag, the slag/gas interface quite locally sinks at the taphole region. The average iron level also drops below the taphole level as a result of the tilting phenomena. If the taphole is not closed at this moment, the hot blast gas leaks out of the taphole.

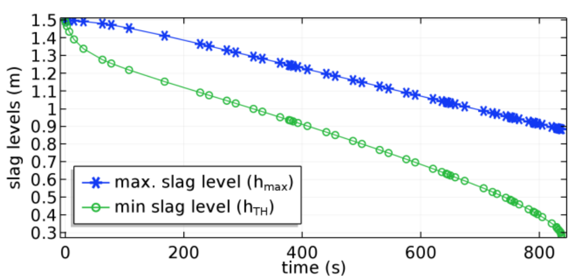


**Figure 4**. The variation of max slag level $h_{max}$ and min slag level $h_{TH}$ (see Figure 3).

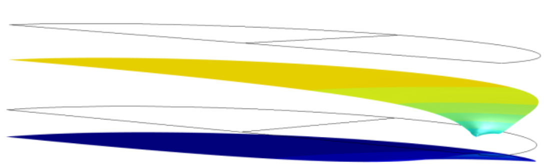

**Figure 5**. Slag/gas and slag/iron interfaces at the end of a tapping cycle.

Besides the basic hearth characteristics (hearth inner radius $R_h$, deadman coke diameter $D_c$ and porosity $\varepsilon_c$), the initial slag layer thickness $H_s$ and slag viscosity $\mu_s$ play important roles on the tilting. The influence of the initial slag layer thickness $H_s$ on the tapping duration is shown in Figure 6. It is clear that the initial slag layer thickness $H_s$ and the tapping duration are linearly correlated. The influence of the slag viscosity $\mu_s$ on the tapping duration is shown in Figure 7. The correlation of the slag viscosity $\mu_s$ and the tapping duration is clearly not linear. The numerical values of the tapping durations are given in Table 1. The slag viscosity $\mu_s$ actually determines how much residual slag will remain in the hearth at the end of the tapping (at similar tapping rates). The initial slag layer thickness $H_s$ has negligible influence on the residual slag remaining in the hearth at the end of the tapping.

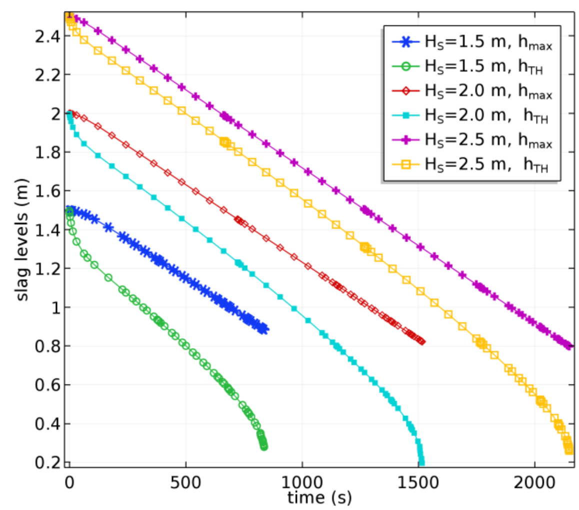


**Figure 6**. Influence of initial slag layer thickness $H_s$ on the tapping duration.

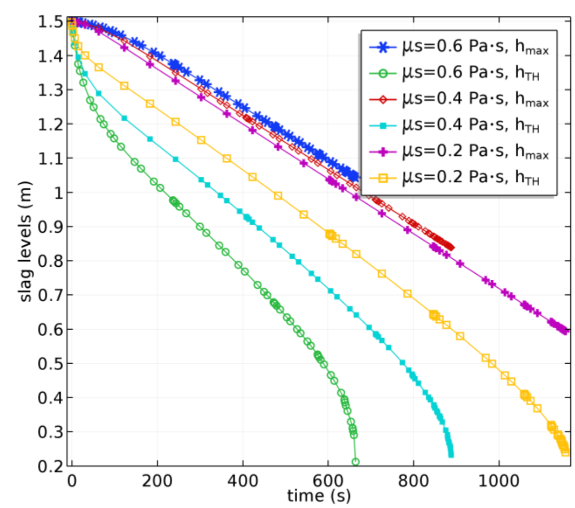


**Figure 7**. Influence of slag viscosity $\mu_s$ on the tapping duration.

For the sake of simplicity, the slag tapping rate is set to double of the production rate $\dot{V}_s$ and similarly iron tapping rate is set to double of the production rate $\dot{V}_i$. However, in practice, the tapping rates can be described by any interpolation function whose data is estimated from operational measurements.

**Table 1:** Tapping duration for various initial slag layer thicknesses $H_s$ and slag viscosities $\mu_s$

| $H_s$ | $\Delta t_{tapping}^{slag}$ | $\mu_s$ | $\Delta t_{tapping}^{slag}$ |
|---|---|---|---|
| 1.5 m | 840 s | 0.6 Pa·s | 665 s |
| 2.0 m | 1510 s | 0.4 Pa·s | 890 s |
| 2.5 m | 2150 s | 0.2 Pa·s | 1150 s |

## Conclusions

A 3D tilting model is developed to estimate the shape of slag/gas and slag/iron interfaces during the tapping process of a blast furnace. The slag/gas and slag/iron interface movements are modelled with moving mesh physics. The so-called viscous fingering (penetration of gas to the taphole) is estimated, which signals the end of the tapping cycle. This model can be used to investigate the influence of model parameters on boundary conditions, hearth geometry, dead man properties, slag properties, tapping rates, etc. Two case studies are performed to demonstrate the influence of the initial slag level and of the slag viscosity on tapping duration. The tilting model has promising perspectives for further development and exploitation of the evaluation of operational data as tapping rates and slag properties to estimated residual slag left in the hearth. As a future work, the authors suggest to introduce local differences and movement of the deadman in the model to allow its usage for a broader range of operation conditions. A direct linkage of the tapping rates to the operational data is also possible to analyze the selected tapping operation in detail. A user friendly app interface can be also implemented to make the model more accessible to the operators and other personal at the blast furnace plant.

## References

1. COMSOL Multiphysics Documentation v4.3b, *Model Library Manual – Sloshing Tank*. (2013)
2. COMSOL Multiphysics Documentation v3.5a, *Model Library Manual – Forchheimer Flow*. (2008)
3. J.v.d. Stel, *et. al.*, *Blast furnace sustained tapping practice*, pages 96-99, RFCS Report EUR 28066, Publication Office of European Union, Luxemburg (2016)

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