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

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Introduction:

The blast furnace is a type of counter current shaft furnace used for iron ore reduction and smelting to produce industrial liquid iron. The end products are molten iron and slag phases tapped from the bottom, and flue gases leaving from the top of the furnace. The blast furnace hearth drainage constitutes a major part of the blast furnace operation. 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.

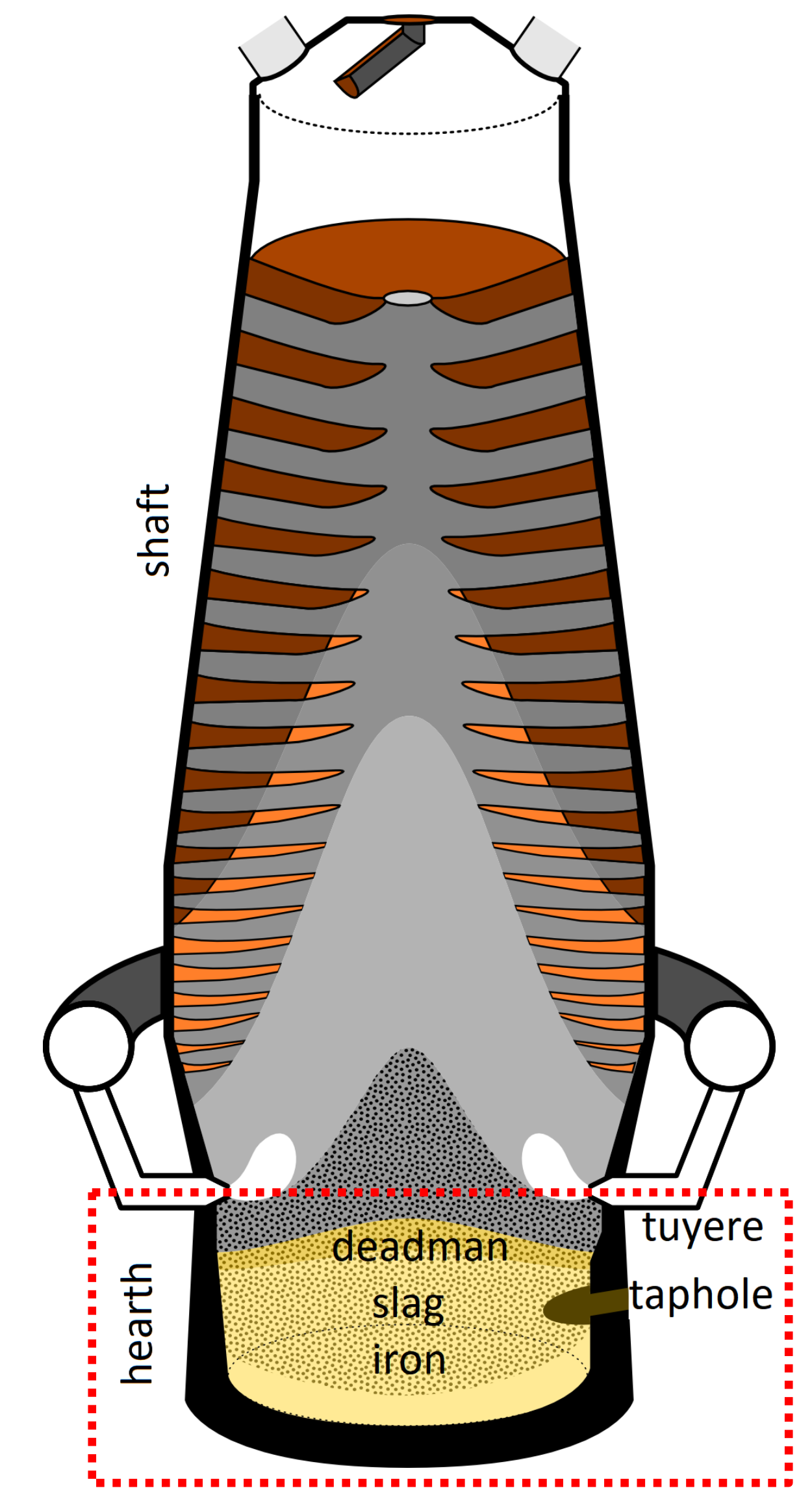

Figure 1. Blast furnace structure

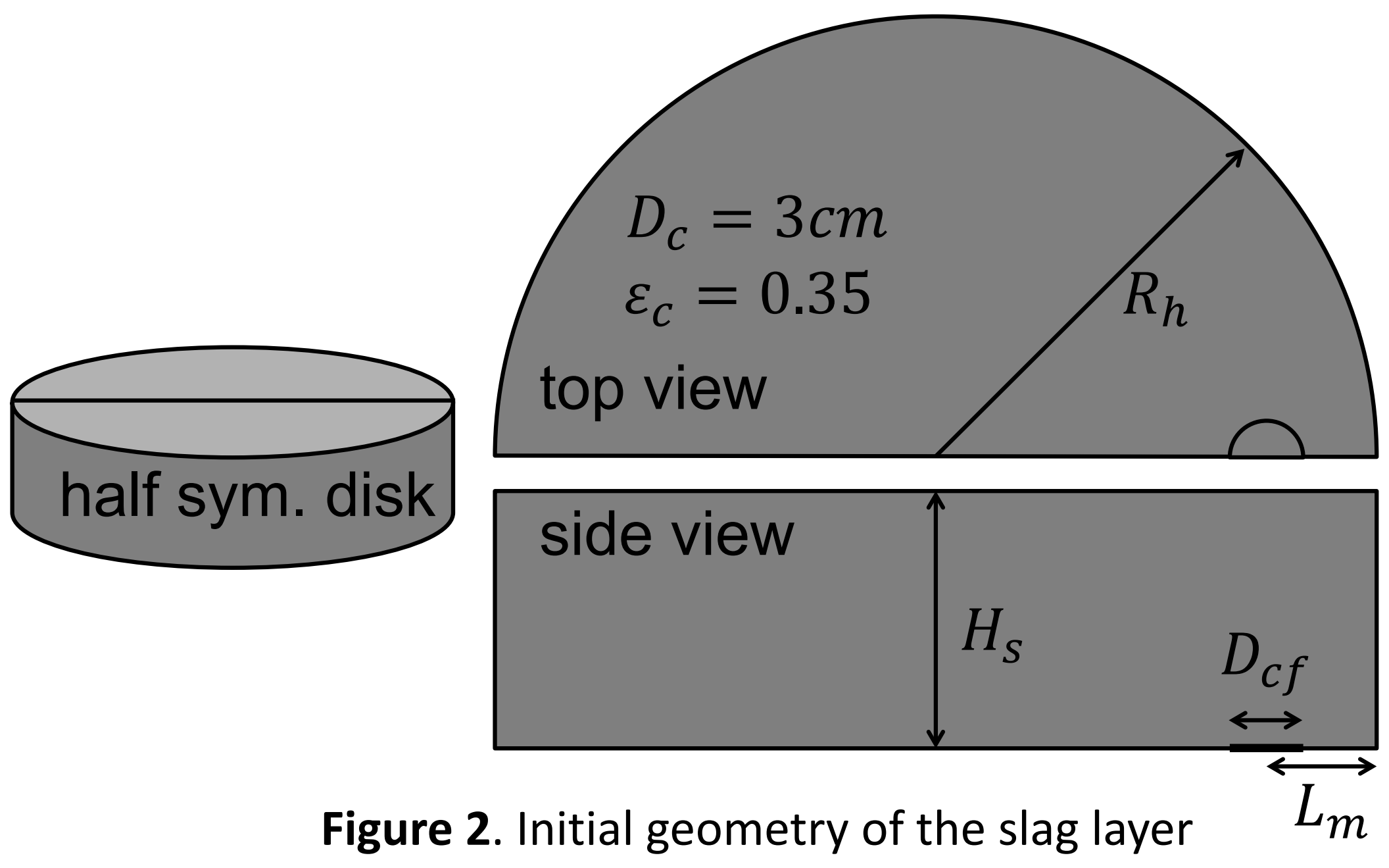

Figure 2. Initial geometry of the slag layer

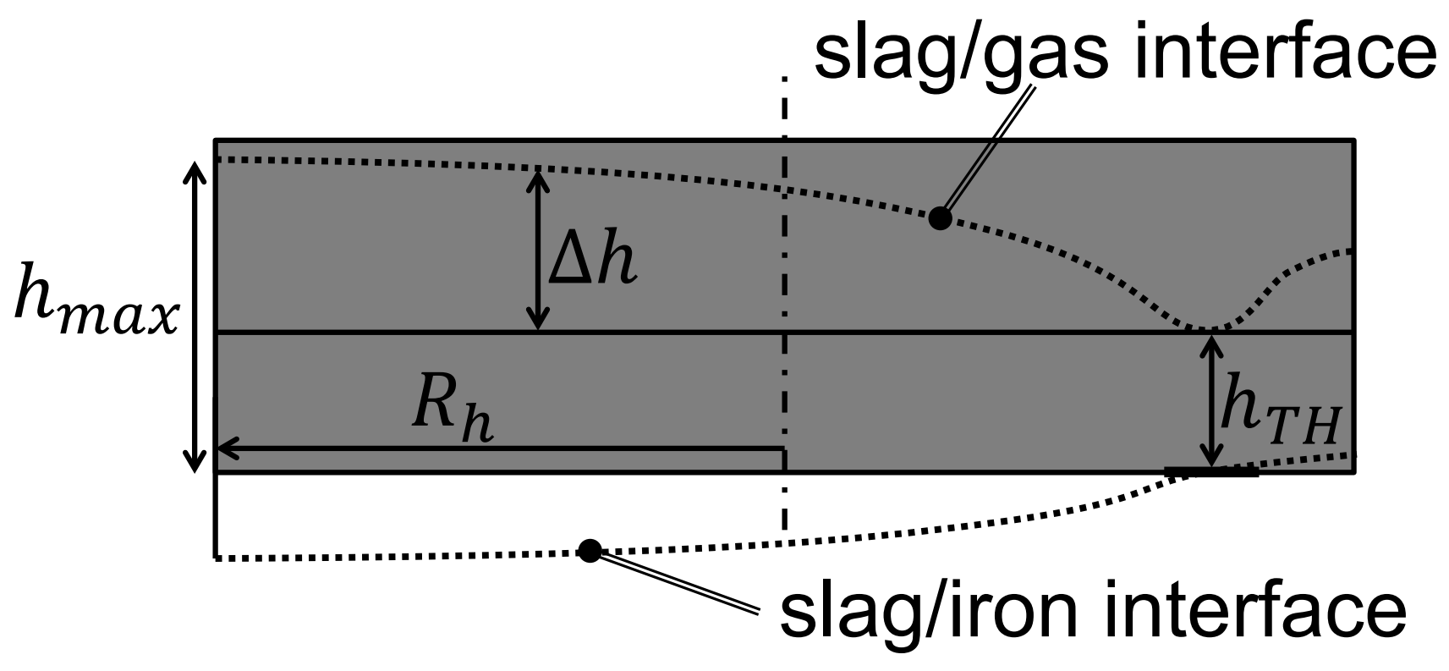

Figure 3. Typical slag/gas and slag/iron interfaces shown at vertical symmetry plane during slag tapping

Computational Methods:

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. 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.

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 as shown in Figure 3 [3]. The complete domain for the slag flow is selected as a porous matrix. Its initial geometry is a half disk as in Figure 2. 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 κ and the Forchheimer coefficients β_F correspond to Ergun's equation:

$$\kappa = \frac{\varepsilon_c^3 \cdot D_c^2}{150(1-\varepsilon_c)^2} \qquad \beta_F = \frac{3.5(1-\varepsilon_c)\cdot \rho_s}{2\cdot \varepsilon_c^2 \cdot D_c}$$

where

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

Slag/gas and iron/slag interface movements:

The slag/gas and iron/slag interface movements are modeled using the "Moving Mesh (ale)". 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 velocity in the normal direction at slag/gas interface is calculated by:

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

where slag level increase due to slag production $w_{s0} = \frac{\dot{V}_s}{\pi R_h^2}$ and slag level decrease due to iron level decrease $w_i = -\dot{V}_i \cdot \frac{\Delta h}{2 \int_S \Delta h \, dS}$.

Results:

The typical shape of the slag/gas and slag/iron interface is shown in Figure 4. The main results, which are most useful to the plant operation, are maximum slag level h_{max} occurring opposite to the taphole and minimum slag level h_{TH} occurring at the taphole entrance (see Figure 3). Furthermore, the influences of the initial thickness of the slag layer H_S at slag arrival and slag viscosity μ_S on the slag tapping duration are discussed in Figure 5, Figure 6 and Table 1.

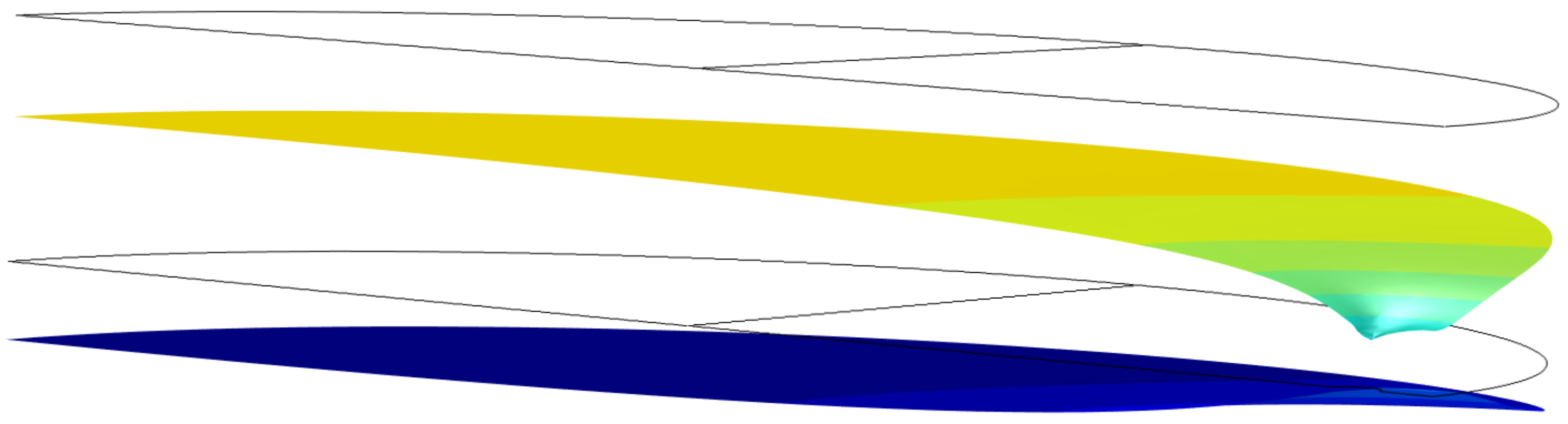

Figure 4. Slag/gas and slag/iron interfaces at the end of a tapping cycle

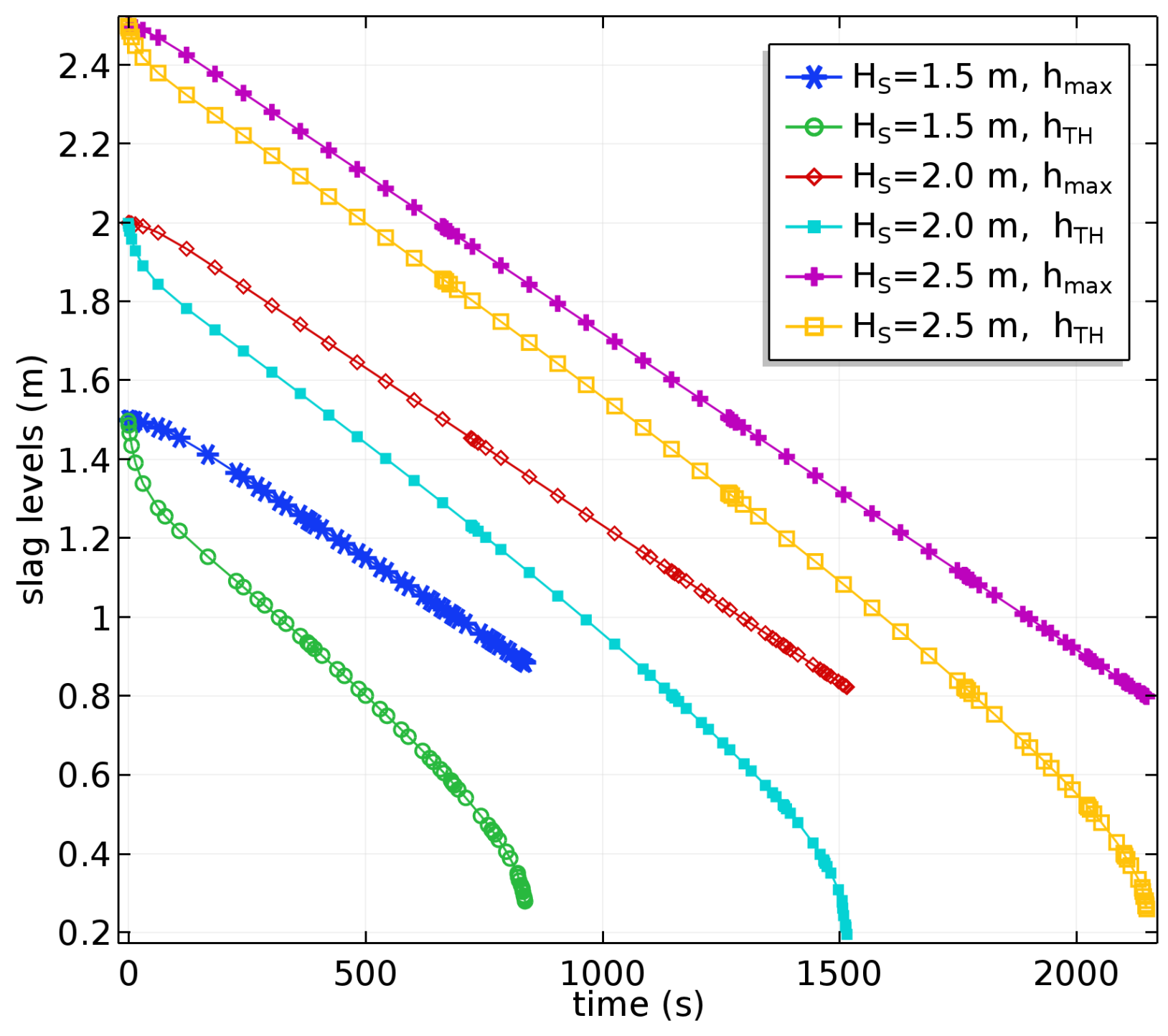

Figure 5. Influence of initial slag layer thickness H_S on the tapping duration

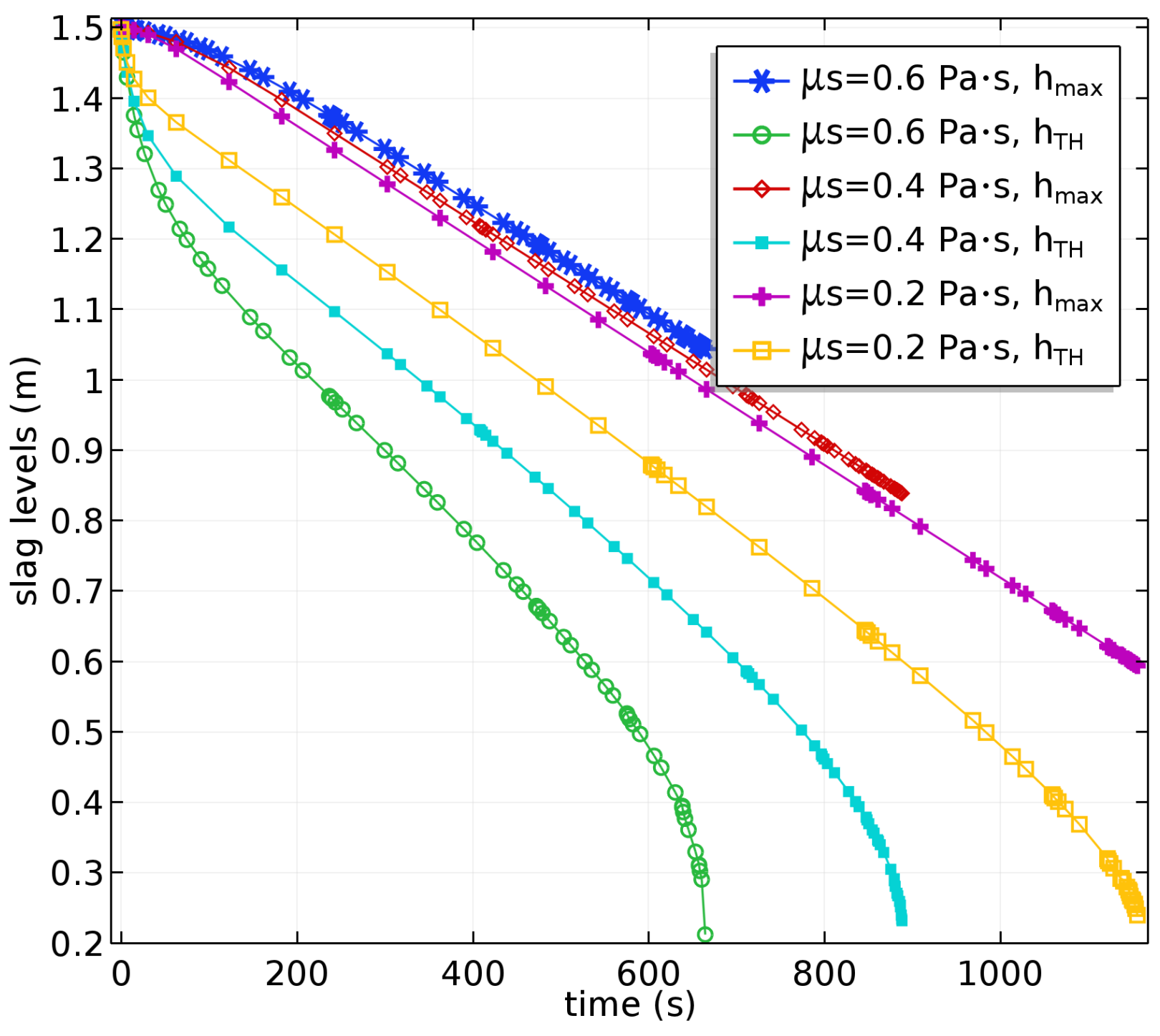

Figure 6. Influence of the slag viscosity μ_S on the tapping duration

H_s	$\Delta t_{tapping}^{slag}$	μ_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

Table 1. Tapping durations for various initial slag layer thickness H_S and slag viscosity μ_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)