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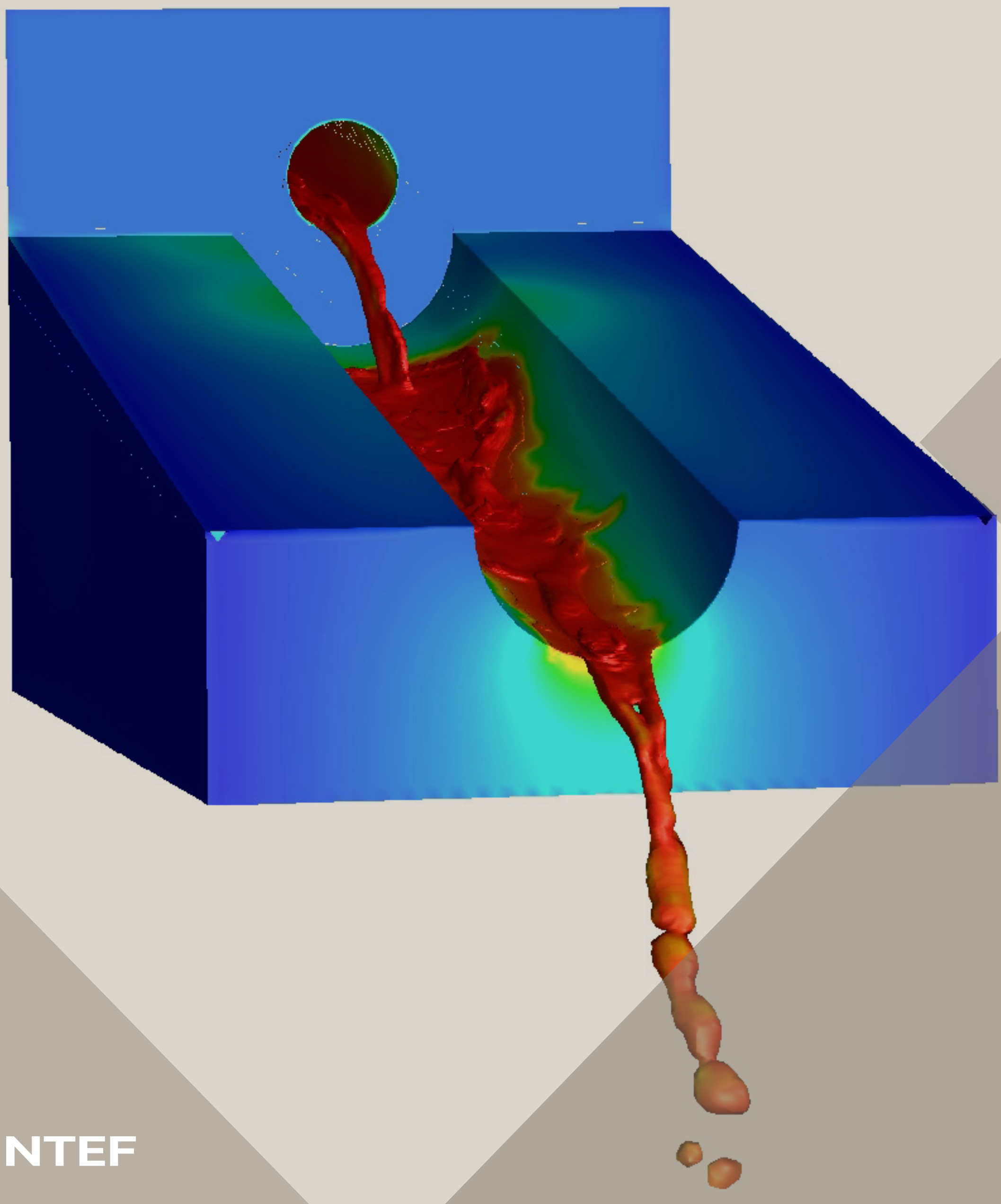

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Editors:
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A CFD STUDY ON THE IMPACT OF BARRIERS AND NONUNIFORMITIES ON FURNACE TAPPING

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ABSTRACT

Tapping of slag and metal from metal producing furnaces are often inconsistent and it is difficult to predict the outcome of the process. Nonuniformities in the particle bed has been hypothesized as reasons for inconsistent tapping of slag and metal. Examples of nonuniformities are cracks in the particle bed, zones with looser packed particles (weak zone) and barriers in the particle bed. The impact of these nonuniformities on the tapping rate have been studied by CFD. The CFD model and results of the study are presented.

Keywords: CFD, metallurgy, furnace tapping.

NOMENCLATURE

Greek Symbols

ρ Mass density, [kg/m^3].

μ Dynamic viscosity, [kg/m.s].

ε Porosity [ ]

Latin Symbols

d Diameter, [m].

P Pressure, [Pa].

v Velocity, [m/s].

Sub/superscripts

p particle.

pb particle bed

s superficial

INTRODUCTION

Furnace tapping is the removal of liquids produced in a furnace. In metal production the liquids are slag and alloy (hereafter referred to as metal). A wide range of different configurations exist depending on which metal is being produced (Nelson and R. Hundermark 2016). Some metals are tapped by suction through a tube (e.g. aluminium), but most metals are tapped by gravity through a tap-hole at the bottom of the furnace. Our main focus is ferroalloys. They are produced in submerged arc furnaces where gravity is the driving force of the tapping. Slag and metal are tapped through a tap-hole into a ladle for further post-furnace processing as illustrated in Figure 1. The grey diffuse area is the particle bed of mineral ore and coke particles. Three electrodes (darker grey) provide energy to run the carbothermic reduction of mineral ore producing slag and metal.

Consistent tapping is desirable for smooth and predictable downstream processing. This is often not the case. The tapping rate varies between different taps and sometimes slag is tapped before metal even though metal is supposed to be tapped first according to the laws of physics. Model studies (mathematical and experimental) have not been able to reproduce this inconsistency. Since these model studies have been performed with uniform conditions in the particle bed, it is hypothesized that nonuniformities or barriers in the particle bed is the cause of inconsistent behaviour. It is very unlikely that the particle bed has a constant particle size and porosity throughout its domain. It will vary.

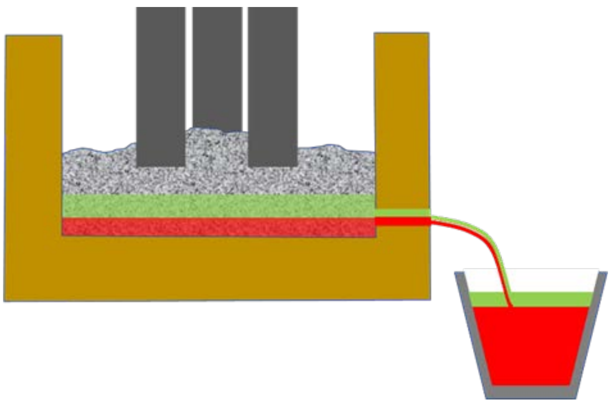

Figure 1: Sketch of furnace with tapping of slag (green) and metal (red).

In this study we apply computational fluid dynamics (CFD) to study tapping rates of slag and metal. CFD has been employed to furnace tapping earlier (Kadhodabeigi, Tveit, and Johansen 2011; Nishioka, Maeda, and Shimizu 2005; Reynolds and Erwee 2017) and validation studies show consistency between model results and experimental results. All of these studies assumed a uniform particle bed in the furnace. This is a reasonable first order approximation, but reality is more complicated. Furnace excavations in connection with furnace shutdown due to maintenance show that the particle bed is not uniform (Ksiazek, Tangstad, and Ringdalen 2016; Ringdalen and Ksiazek 2018). There are regions with an impenetrable material formed by different accumulated elements including graphite, titanium carbide, slag and other. They particularly form around the periphery of the furnace. If they form at the furnace bottom or break off from the furnace periphery and fall to the bottom, they can form barriers for flow of liquid slag and metal. Also, there can be cracks in the particle bed or nonuniform particle distribution close to the tap-hole. This can be caused by the opening and closing of a tap-hole. Tap-holes are closed by injecting tapping clay with a mud gun. It is opened again by drilling through the tapping clay. Both these operations exert a significant force on the materials close to the tap-hole which will reconfigure the particle structure. It is hypothesized that this reconfiguration is significant enough to change the morphology of the particle bed close to the tap-hole which will not be uniform. Such deviations from the assumption of a uniform particle bed may impact the tapping rates of slag and metal. CFD is here applied to furnace tapping with barriers and nonuniformities in the particle bed.

CFD MODEL

Furnace tapping is conceptually similar to drainage of tanks which is often used as modelling examples in introductory classes in fluid mechanics and mathematics. Compared to classic tank drainage, furnace tapping is complicated by the granular material (ore, coke, …) which forms a particle bed in the furnace. The granular material provides resistance to drainage and this needs to be accounted for in mathematical models for furnace tapping. Within the CFD-framework of models, there are three different methods to account for the granular material. These are the coupled Navier-Stoke's and discrete element method (DEM), the Eulerian multiphase model with a granular phase and the porous zone model. Here we have chosen to apply the porous zone model available in the commercial CFD-software ANYS/Fluent r19. The model allows for sharp interface tracking between the different phases which is not possible in the Eulerian multiphase model. The DEM approach is computationally too expensive if a typical number of particles in a furnace needs to be tracked.

The porous zone model solves for conservation of mass and momentum with the continuity equation and the Navier-Stokes equations respectively. The phases are immiscible, and their motion is governed by one common momentum equation which applies material properties according to the phase material present locally. The phases are separated by interfaces which are tracked with the Geo-Reconstruct scheme. The porous zone model accounts for the granular material by adding a sink term in the momentum equation which provides resistance to the flow. This is described as a pressure drop. We apply the Ergun equation (Ergun 1952) for this pressure drop ΔP_{pb} through the particle bed

$$\frac{\Delta P_{pb}}{\Delta L} = \frac{150\,\mu}{d_p^2}\frac{(1-\varepsilon)^2}{\varepsilon^2}v_s + \frac{1.75\,\rho}{d_p}\frac{(1-\varepsilon)}{\varepsilon^3}v_s|v_s| \qquad \text{Eq. 1}$$

Here ΔL is a length increment in the particle bed, μ is liquid viscosity, ρ is liquid density, ε is particle bed porosity, d_p is particle diameter and v_s is the superficial liquid velocity through the particle bed. Such a model can be applied to study how barriers and nonuniformities in the particle bed affects tapping from the furnace. In the following sections we demonstrate how the model compares with experimental results (model validation) and how some nonuniformities and barriers affect the tapping rate.

Model Validation

The model is compared against the drainage experiment of Vångö, Pirker, and Lichtenegger (2018). The experiment was performed in a 400 mm tall tank with a footprint of 330 x150 mm. Wood chips were used as granular material. After a while they became saturated with water and achieved an equivalent radius of 6.5 mm. Water was filled up to a level of 300 mm. The authors did not specify the height up to which the tank was filled with wood particles. By assuming a packing porosity of 0.4, which is quite typical we get a particle bed height of 200 mm. The experiment is illustrated in Figure 2. Two simulations with the model were performed: one with a porous zone up to 200 mm representing the wood particles and one without a porous zone. The simulation accounting for the particle bed (porous zone) produces results on the tapping rate which is very consistent with the experimental measurements. This is seen in Figure 3. Note that the assumption of a packing porosity of 0.4 affects the result. The assumption is reasonable, but it still is an assumption. However, any deviation from 0.4 will not discredit the consistency. The consistency might change from very good to fairly good. The simulation neglecting the particle bed (no porous zone) gives a higher tapping rate and faster tapping. This is as expected since the particle bed is supposed to provide resistance to the flow.

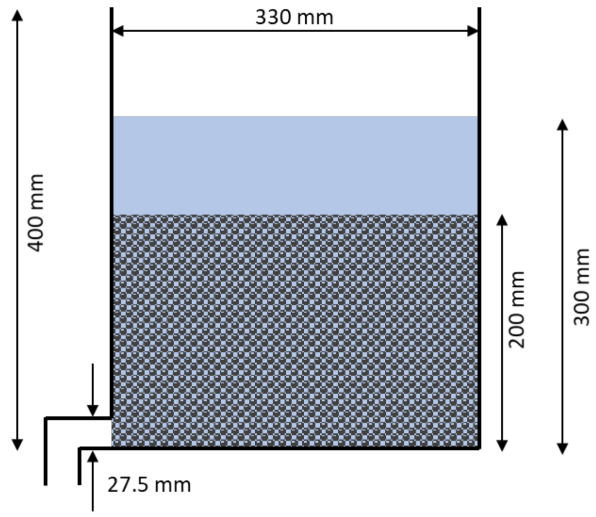

Figure 2: Sketch of drainage experiment

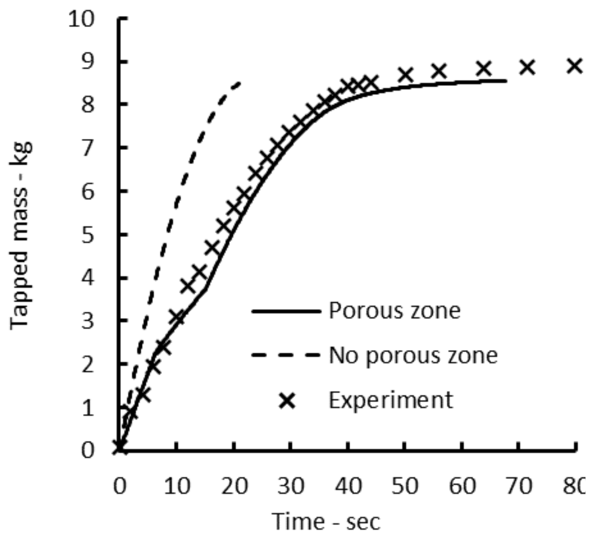

Figure 3: Tapped mass as function of time based on experimental measurements and simulation results with and without a porous zone.

SIMULATIONS OF NONUNIFORM FURNACE CONDITIONS

As mentioned above, nonuniform conditions in the furnace can impact the tapping rates. The effect from some examples are investigated here.

Structural inhomogeneities near tap-hole

When the tap-hole is opened, the structural integrity of the packed bed of materials close to the tap-hole entrance is destabilized. This may lead to cracks in the particle bed or a nonuniform distribution of the particles.

A CFD analysis on two potential nonuniform conditions have been carried out. These have been compared against a base case of uniform condition. In a uniform condition, the particles are evenly distributed inside the container representing a furnace. This volume is described by a constant porosity with particles of constant size. The tap-hole is represented with a cylindrical exit tube where no particles are present. The geometry is illustrated in Figure 4 with boundary conditions. At the top there is a pressure inlet condition where a driving pressure can be applied. At the tap-hole outlet, there is a pressure outlet condition. Three phases are accounted for: metal, slag and gas with properties as listed in Table 1. The CFD model applies the VOF algorithm to account for the interfaces between the faces. For the initial configuration, the amount of metal is varied. This is specified with a height or level of metal above the furnace bottom. The initial slag level (i.e. height of gas-slag interface) is kept constant which due to the varying initial metal level results in a varying initial amount of slag.

Typical results are seen in Figure 5 illustrating the different phases. We see a typical uplift of metal towards the tap-hole due to the driving pressure from the weight of the slag phase and the gas phase pressure. At the outlet of the tap-hole there seem to be a well-defined layer of slag above the metal as seen in Figure 6.

Two types of nonuniformities are defined here. One is a crack in the particle bed where fluids can flow freely without porous resistance. This is illustrated in Figure 7. The other is a weak zone on the upper neighbourhood of the tap-hole. The opening of the tap-hole can cause some collapse in the region which will lead to looser packing of the material. This zone is illustrated in Figure 8 and the weak zone is modelled with a porosity of 0.5 compared to 0.4 elsewhere.

Table 1: Modelling conditions.

Metal density:	6100 kg/m3
Metal viscosity:	0.005 kg/m s
Slag density:	3000 kg/m3
Slag viscosity:	0.1 kg/m s
Gas density:	0.5 kg/m3
Gas viscosity:	0.00005 kg/m s
Tap-hole diameter:	10 cm
Tap-hole length:	1 m
Height of tap-hole centre line:	15 cm
Initial height gas-slag interface:	0.5 m

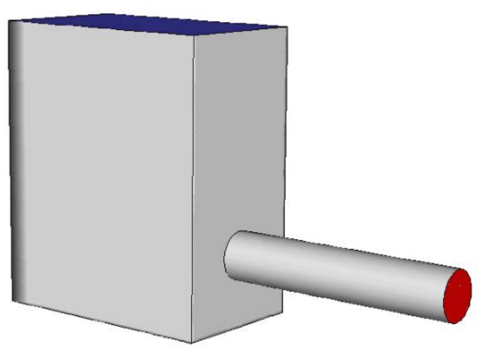

Figure 4: Model geometry with boundary conditions

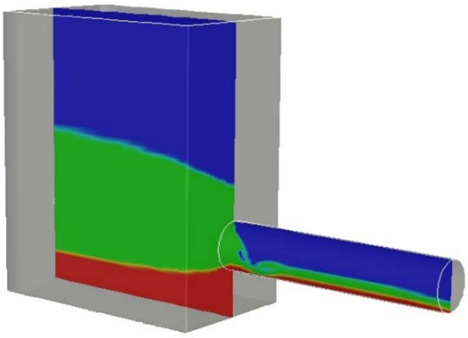

Figure 5: Contours of metal (red), slag (green) and gas (blue) phases during tapping

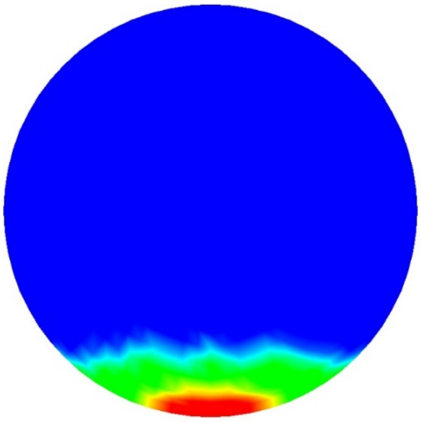

Figure 6: Contours of metal (red), slag (green) and gas (blue) phases at tap-hole outlet

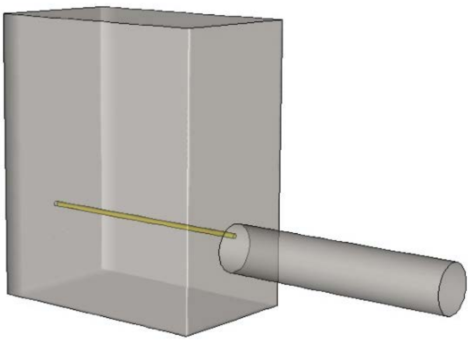

Figure 7: Geometry with crack (yellow)

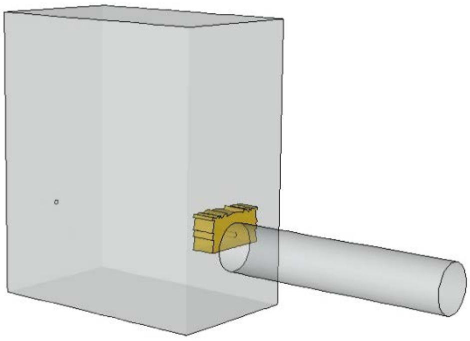

Figure 8: Geometry with weak zone (yellow)

Quantitatively there is some sensitivity on the tapping rates with respect to nonuniformities. A typical evolution of tapping rates as function time is seen in Figure 9. The cases shown are for an initial level of 10 cm of metal which covers up to lower level of the tap-hole. The tapping rates peak shortly after tap-hole opening before it decreases almost linearly with time. In Figure 10 the peak tapping rates are plotted for various values of initial metal levels. We see that the initial metal level has a significant impact on the tapping rates. The impact of a crack is almost insignificant, but a weak (or loose) zone close to the tap-hole affects the tapping rate of the slag phase in particular. Since the weak zone is in the upper part of the inflow towards the tap-hole it is natural that it mostly affects the slag flow. Note that for high levels of metal, the tapping rate of metal is also affected. This is caused by metal now being present in the weak zone.

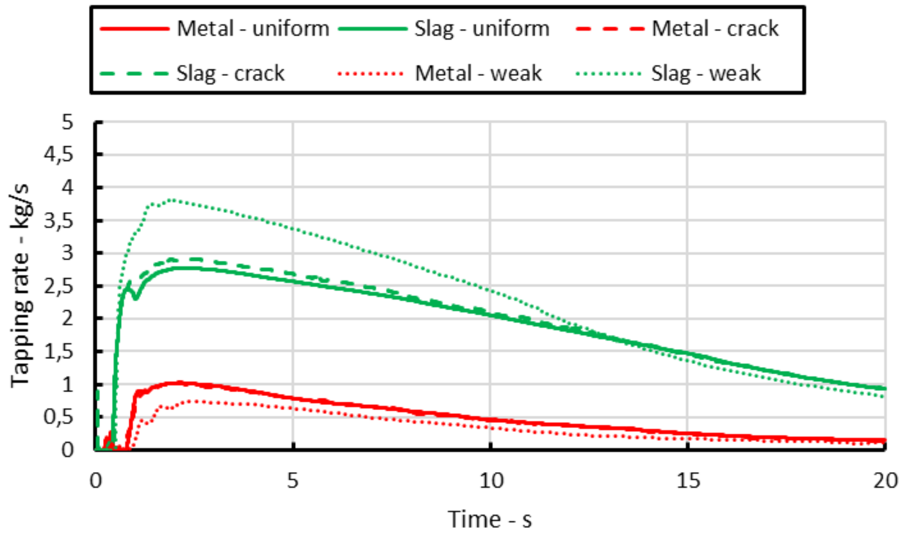

Figure 9: Tapping rates of slag and metal for initial metal height of 10 cm above furnace bottom.

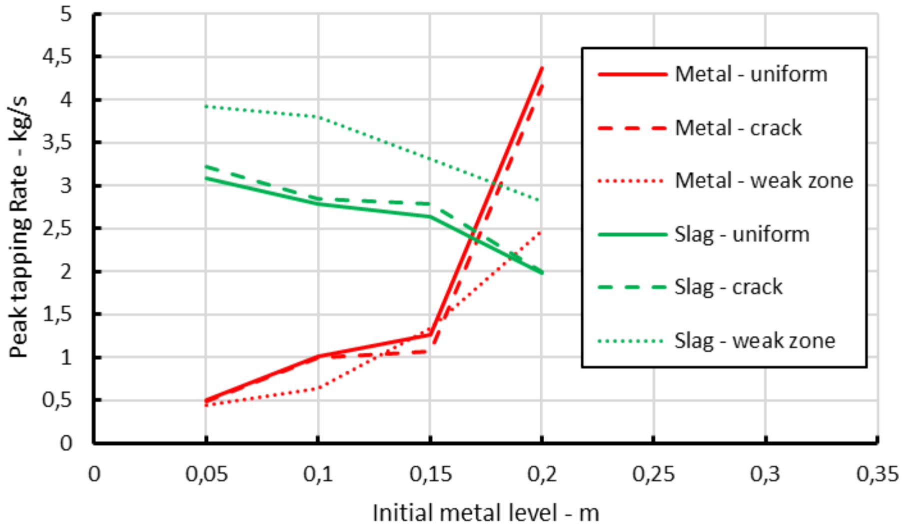

Figure 10: Tapping rates of slag and metal

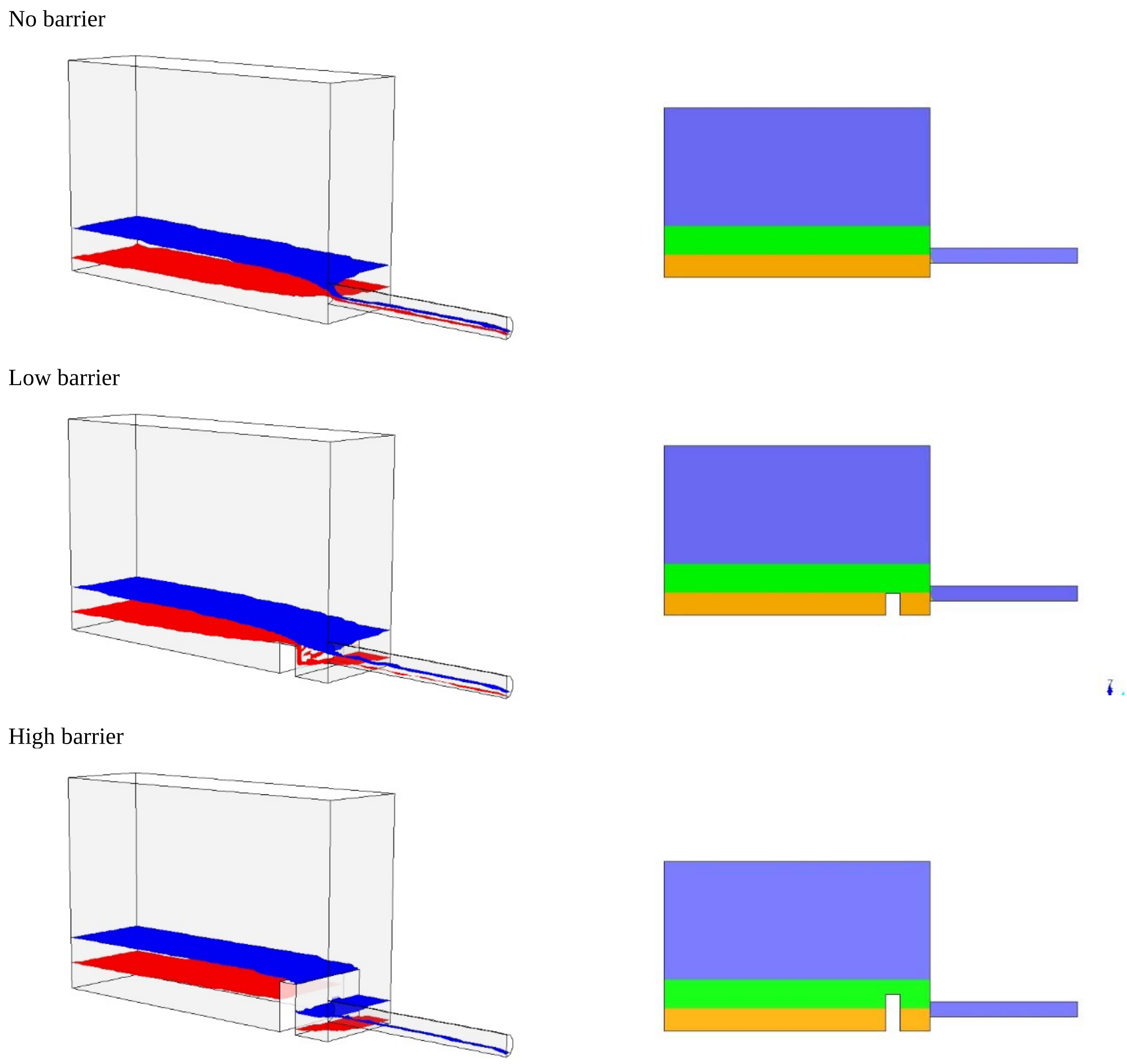

Figure 11: Tapping of slag and metal with and without barriers. Left side shows interface between gas and slag (blue) and metal and slag (red) during tapping. Right side shows initial filling of slag (green) and metal (orange).

Barriers near tap-hole

Barriers near the tap-hole will affect the flow of slag and metal towards the tap-hole and the respective tapping rates of slag and metal.

A CFD study has been conducted where two barriers (one low and one high) have been positioned in front of the tap-hole. This is illustrated in Figure 11. Since the barriers are resting on the floor of the furnace, they mostly affect the flow of the lower liquids which tend to be the metal phase.This can be assessed by analysing the resulting tapping rates of slag and metal.

Tapping rates of slag and metal are plotted in Figure 12. We see that the tapping rates are affected by the barriers. The metal rate is reduced by the barriers and slag rates are increased. The high barrier reduces metal rate more than the low barrier. However, metal has the highest initial peak rate regardless of barriers.

What happens if the barriers also block access to the region in front of the tap-hole for metal to fill up this part prior to opening of the tap-hole? Two simulations were run with such initial conditions. The initial conditions are illustrated in Fig.13 and the results are shown in Fig.14. The results show that for the low barrier, metal tapping is delayed and only slag leaves the tap-hole initially. For the high barrier, no metal leaves the tap-hole. The metal production rate and/or tapping interval needs to be sufficient for the initial metal level to either overflow the barrier or at least be close enough for the driving pressure to lift the metal level above the barrier. As metal accumulates, metal will flow over the barrier and start to tap. Then only the metal beneath a certain level will be disabled for tapping. All metal produced after this level is reached will be tapped.

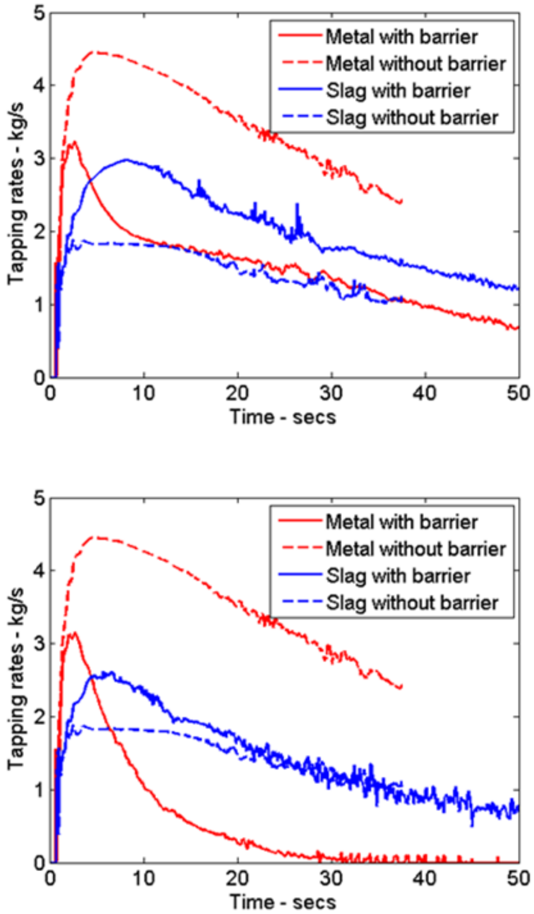

Figure 12: Tapping rates for metal and slag with low barrier (top) and high barrier (bottom) in front of tap-hole compared against tapping rates without barriers.

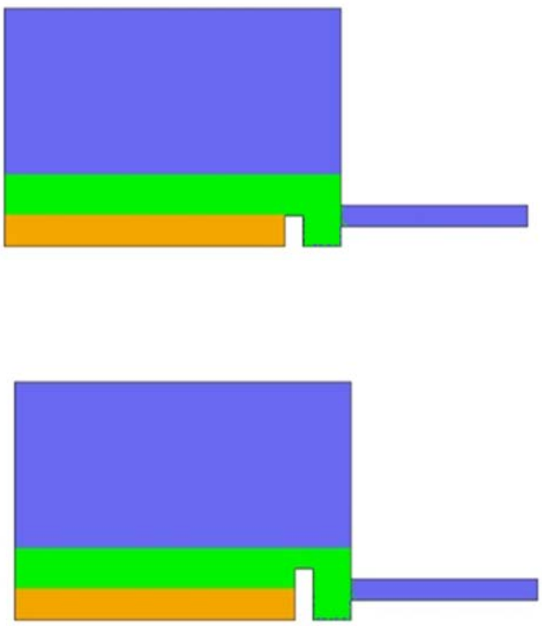

Figure 13: Initial slag and metal filling when barriers block filling of metal in front of tap-hole. Low barrier at the top and high barrier below.

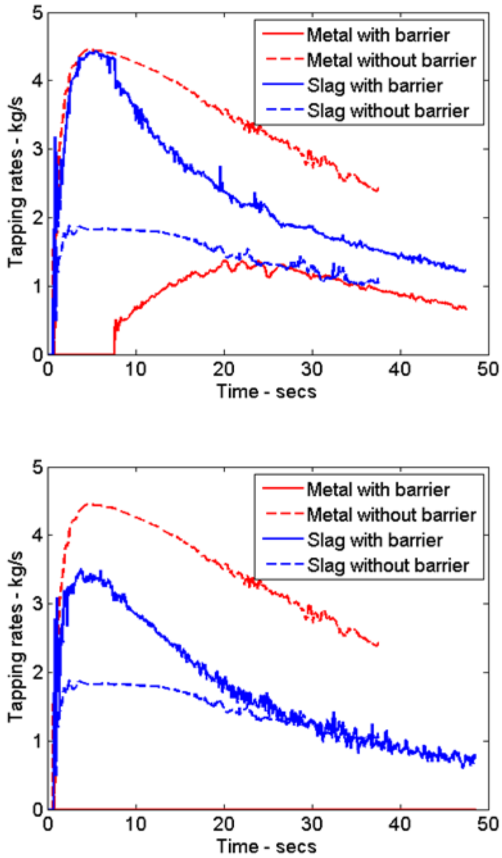

Figure 14: Tapping rates for metal and slag with low (top) and high barrier (bottom) in front of tap-hole when barrier blocks filling of metal in front of tap-hole compared against tapping rates without barriers.

CONCLUSION

Nonuniformities in the particle bed has been hypothesized as reasons for inconsistent tapping of slag and metal. Examples of nonuniformities are cracks in the particle bed, zones with looser packed particles (weak zone) and barriers in the particle bed. The impact of these nonuniformities on the tapping rate have been studied by CFD. A crack (as defined in this study) has little impact on the tapping rates. A zone with looser packed particles (weak zone) close to the tap-hole has a more significant effect on the tapping rate. If a barrier blocks drainage of one or two phases towards the tap-hole, tapping might be hindered or delayed for the phase being blocked. This can cause slag to be tapped before metal, which is unusual, but sometimes observed. A barrier has a significant impact on tapping rates.

The study shows that the nonuniformities studied to different degrees affect the tapping rates of slag and metal. Some of these nonuniformities can easily change between consecutive taps and thus cause inconsistent tapping. Barriers will most likely not change that frequently and are thus probably not the cause for inconsistency between consecutive taps. They may explain inconsistency over longer time spans. More studies on nonuniformities can easily be performed by this method provided insight on particle bed configuration and nonuniformities defines interesting cases. The model complexity and realism can be increased by introducing heat transfer and phase change. This requires a fair bit of extra work. These mechanisms will probably add randomness to the tapping process and strengthen the trend of inconsistent tappings.

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