Off-line Model of Blast Furnace Liquid Levels

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An off-line simulation model of the blast furnace hearth is developed based on mass balances for iron and slag, expression of the liquids outflow rates and logical conditions for the start and the end of the outflow of liquids. The dynamic model divides the furnace hearth into two regions of sizes that may change during the tapping process. It provides a description of the time evolution of the liquid levels and predicts the duration and the periods of iron- or slag-only flow in the beginning of the taps. The values of some model parameters are estimated on the basis of measurements in a reference blast furnace, while others are fixed. A sensitivity analysis of the model is provided, revealing the role of some key parameters. The model is demonstrated to describe the overall drainage behavior of the reference furnace reasonably well, and the presence of pools with different liquid levels can also be deduced from the real data. Finally, some recommendations for future work are suggested.

KEY WORDS: blast furnace hearth; drainage; liquid levels; iron and slag tap rates.

1. Introduction

The operation of the lower part, the hearth, plays a crucial role for the blast furnace (BF) as it is the region where the liquid products, hot metal (also called pig iron) and slag, accumulate before they are drained through the tapholes.1) The state of the hearth is also important as long furnace campaigns extending up to 20 years are aimed at with limited possibilities to repair the lining before the final blow-out.2) The hearth drainage process is complicated by the presence of a coke bed, the deadman, through which the liquids have to flow during their passage, and by the fact that the two liquid phases are drained through the same taphole. However, periods of one-phase flow may occur initially, followed by two-phase flow in the later parts of the tap. Since the tapholes cannot be kept open for longer periods as this would lead to excessive wear of the taphole lining, the furnace has to be tapped intermittently. In larger furnaces with several tapholes, the tapping operation can be practically continuous, but a cycling motion of the liquid levels in the hearth cannot be fully avoided because of variation in the tapping speed of the liquids. In summary, the blast furnace tapping process is complicated and appropriate control of the draining process requires fundamental understanding of the underlying phenomena.3,4)

The outflows are driven by the in-furnace gauge pressure that balances the pressure drops induced by liquid flows through the deadman and taphole. As iron and slag drain simultaneously, the high viscosity of the slag decreases the static pressure in front of the taphole, which makes it possible to drain iron to levels well below the taphole.5) The slag viscosity also gives rise to a downward bending of the slag-gas interface toward the taphole, which leaves considerable amounts of residual slag in the hearth as the tap ends when gas bursts out from the taphole.6,7) These phenomena make the time evolution of the liquid levels during the tap cycle complex. Furthermore, in large furnaces the liquid levels may be fundamentally different in the region close to the draining taphole and on the opposite side, particularly if the deadman voidage is low, e.g., due to impermeable zones8,9) caused by poor coke quality or by coke fines that accumulate in the bed because of improper combustion of excessive injection rates of pulverized coal.10)

The draining of the blast furnace hearth has been studied by many authors in the literature and several models have been proposed to shed light on the internal conditions, including liquid levels and deadman state, and the outflows of iron and slag. Tanzil et al.3) were the first investigators to point out the fact that iron could be drained to levels below the taphole because of a simultaneous outflow of the more viscous slag phase. They applied a slot model with two immiscible liquids to demonstrate the theory and also discussed the bending of the slag surface at the end of the tapping, revising the original findings of Fukutake and Okabe.6,7) Zulli11) further refined the expression of the residual slag, considering the motion of the iron-slag and slag-gas interfaces. Later, Nouchi et al.12) experimentally studied the influence of different deadman voidages, including cases where the core of the deadman was clogged, on...
hearth drainage and the outflow rates of the two liquids. Nightingale and Tanzil\textsuperscript{13} developed a simple conceptual model of how the liquid levels vary and, on the basis of the findings of Tanzil et al.,\textsuperscript{5} proposed a model that could estimate the deadman voidage from the observed slag delay, \textit{i.e.}, the duration of the iron-only flow in the beginning of the tap. Based on a similar approximation of how the liquid levels evolve, Brännbacka et al.\textsuperscript{14} developed a set of simplifying algebraic equations for hearth draining in one-taphole furnaces and extended the work from a hearth with a sitting deadman to the floating deadman case. Brännbacka and Saxén\textsuperscript{15,16} demonstrated based on slag-delay data from two blast furnaces that the same basic approximations could reveal whether the deadman sits (partially) floats.

More detailed simulation models of hearth drainage have also been proposed. Nishioka et al.\textsuperscript{17} developed a three-dimensional simulation model by which the drainage of a blast furnace hearth was simulated under different conditions. A simpler drainage model was presented by Shao and Saxén\textsuperscript{18} who considered simplified expressions of the overall liquid levels in the hearth, but also included a model of the taphole where the two liquids were assumed to remain stratified. Iida et al.\textsuperscript{19,20} studied a blast furnace with several tapholes, and discussed the role of impermeable zones. They developed a model which considered the general evolution of the liquid levels, using two or three pools to explain the observed drainage behavior in a large furnace. Saxén\textsuperscript{21} proposed a steady-state model of a two-pool hearth of a blast furnace with two (operating) tapholes and simulated and discussed the role of pool interconnection on the evolution of the liquid levels. However, the tapholes were taken to be plugged for a longer period, so iron was always the first phase to flow out when the taphole was opened. Some attempts have also been made to describe the complex hearth draining by a combined CFD-DEM approach.\textsuperscript{22,23} Vångö et al.\textsuperscript{24} also addressed the drainage problem of the blast furnace hearth and pointed out some fundamental numerical problems that still must be solved in using this sophisticated technique to describe the interaction between fluids and particles.

Even though the understanding of the draining process of the blast furnace hearth has advanced along with application of small-scale model experiments and sophisticated numerical modeling tools, there is still a considerable knowledge gap that has to be filled before the tapping process can be understood sufficiently to design appropriate liquid level control schemes. In order to gain better understanding of the complex patterns in a blast furnace with two alternately operating tapholes, a simple model of the liquid levels and draining of iron and slag has been developed. The model is inspired by earlier models developed for one-taphole furnaces,\textsuperscript{14,18} for furnaces with multiple tapholes\textsuperscript{19-21} and by measurements from a reference furnace with three tapholes. A new way of dividing the furnace hearth into regions of dynamically changing size is proposed. The model is illustrated by a sensitivity analysis where some of its parameters are varied and the resulting liquid levels are studied. Particular attention is also given to the slag delay. The model is demonstrated to be able to explain some observations of the outflowing liquids in the reference furnace.

2. The Model

2.1. Background

Multiple taphole furnaces may be tapped according to different strategies and as the tapholes have to drain a larger region, the outflow rates may vary considerably with time along with the arrival of liquids of different temperature and viscosity to the taphole. Earlier analysis by the present authors focused mainly on the conditions in one-taphole furnaces, where the slag delay ($\Delta_d$) was demonstrated to be an interesting indicator characterizing the liquid levels.\textsuperscript{14,15} In larger furnaces the period during which both tapholes are plugged simultaneously is usually very short, and the iron-slag interface may not have time to ascend above the level of the other taphole. As a result of this, there may be tappings where slag enters the runner first, followed by iron after some time,\textsuperscript{17} which could be termed taps with “negative slag delays”. However, along with an increase in the taphole diameter, the longer flow paths of the liquids make it likely that the liquid levels in different parts of the hearth deviate from each other. An approach is here made to extend the analysis to BFs operating with two alternating tapholes. For this purpose, a simplified off-line simulation model was developed, describing the time evolution of the liquid levels in the hearth. For the sake of brevity, in what follows the vertical level of the iron-slag and slag-gas interfaces are called the “iron level” and “slag level”, respectively. To make the model fast, it is not based on computational fluid dynamics but instead applies a simplified description of the conditions in the hearth coupled with a parameterized expression of the liquid outflow rates inspired by practical findings in a reference plant. The hearth is, like in the models proposed earlier,\textsuperscript{19-21} divided into pools as indicated in Fig. 1.

2.2. Main Assumptions and Equations

The mathematical model is based on the following main assumptions:

1. The hearth is divided into two pools, with individual levels of iron and slag.
2. The size of the two pools may vary during the tap.
3. The pools communicate with liquid flows proportional to the pressure difference in the pools, controlled by two communication factors ($\varphi_u$ and $\varphi_d$).
4. The inflow rates of iron and slag to the hearth, $\dot{m}_t$, are given
5. The outflow rates show a fast initial increase, followed by a gradual increase
6. The tap ends when the slag level in the draining pool bends down to the taphole.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Fig1.png}
\caption{Two-pool model of blast furnace hearth with (at least) two tapholes. Left: vertical cross-section. Right: Horizontal cross-section. The length of the dividing wall is $L$.}
\end{figure}
7. The height of the overall slag level above the taphole is connected to the depth of the overall iron level below the taphole in the draining pool.

In the following, the assumptions are justified and their implications are treated at some length. A multi-pool treatment of the hearth was proposed by Iida et al., who applied a two- or three-pool model to explain some practical observations in the operation of a large blast furnace, including the evolution of the liquid outflow rates and the drainage of slag from different tapholes. For the sake of simplicity, we divide the furnace into two pools only, but the treatment of them as dynamic entities makes it possible to realize different behavior of the pools: In particular, a growing pool size will lead to faster initial decrease in the liquid levels (in the draining pool), which is supported by observations of the slag delay in the reference plant. We assume that the cross-section area of the hearth, \( A = \pi d^2 / 4 \), where \( d \) is the hearth diameter, is divided into two complementary parts, the shares of which vary. The area of Pool 1 grows from \( A_{\text{min}}(1) = s_{\text{min}}(1) A \) to \( A_{\text{min}}(2) = \left( 1 - s_{\text{min}}(2) \right) A \) when Taphole 1 is operated, where two parameters representing the minimum shares of the pools are introduced, \( s_{\text{min}}(1) \) and \( s_{\text{min}}(2) \). Conversely, when Pool 2 is tapped, its area grows from \( A_{\text{min}}(2) = \left( 1 - s_{\text{min}}(2) \right) A \) to \( A_{\text{min}}(3) = \left( 1 - s_{\text{min}}(3) \right) A \). The monotonous area changes between the extremes are described as sigmoidal transitions in time, \( \sigma(t) \), from the minimum share to the maximum share of the pool according to

\[
s^{(i)}(t) = s_{\text{min}}^{(i)} + \sigma(t) \left( s_{\text{max}}^{(i)} - s_{\text{min}}^{(i)} \right)
\]

where \( t_{\text{min}} \) is the time of the tap start (i.e., when the first liquid flows out of the taphole), and \( s_{\text{max}}^{(i)} \) and \( C \) are factors determining range and duration of the transition.

The mass flow \( \dot{m}_{l}^{(12)} \) of iron (subscript \( i = \text{ir} \)) and slag (subscript \( i = \text{sl} \)) from Pool 1 to Pool 2 is taken to be proportional to the length \( L \) of the permeable “wall” between the pools (cf. Fig. 1) and the difference of the pressure prevailing in the bottom of the pools, so \( \dot{m}_{l}^{(12)} = \varphi L \Delta p_{l}^{(12)} \), \( i = \text{ir}, \text{sl} \) .................................. (2)

where \( \varphi \) is a parameter that can be adjusted in the model. As discussed in the Introduction, the flow of the viscous slag gives rise to a pressure drop which can lift the iron from levels below the taphole.5) In the model, the lifting effect was taken to be proportional to the slag outflow rate, imposing an upper limit on how much the iron level could be lifted in the beginning of the tap. Even though this treatment is very approximate, it serves to eliminate very negative slag delays that the model would yield without this condition.

It is generally accepted that the bending of the slag surface against the taphole eventually makes gas escape through the taphole, which ends the tap. To estimate when this happens, several investigators have studied the system in laboratory scale and proposed correlations, e.g., for the flow-out coefficient \( 5,7,11 \)). Factors affecting the amount of residual slag are the slag outflow rate, slag viscosity, deadman voidage and coke diameter. As most of these (local) properties are unknown in the practical operation of the blast furnace, a simplified tap-end condition was applied here.
the left part of Fig. 2 by the dashed-dotted line. K "gain" factor sition in the updated expression for the iron outflow rate -towards the inflow rate through a gradual (sigmoidal) tran the outflow rate of iron obtained from Eq. (4) is changed iron level may descend: when this limit is approached. Tanzil et al.3) derived a limiting condition linking the end levels of slag and iron through a pressure balance over the system, yielding

\[
\frac{z_i^f - z_h^f}{z_i^l - z_h^l} = \frac{m_i}{\rho_i} \frac{\rho_i}{\rho_h - \rho_i} \tag{5}
\]

In the present model, a condition for the (final) iron level in the draining pool was imposed through

\[
\Delta z = \min\left( \frac{m_a}{\rho_a - \rho_i} \left( \frac{z_i^{f\prime} - z_h^{f\prime}}{z_i^l - z_h^l} \right), \Delta z_{\text{max}} \right) \tag{6}
\]

Equation (7) influences how far below the taphole the iron level may descend: when this limit is approached the outflow rate of iron obtained from Eq. (4) is changed towards the inflow rate through a gradual (sigmoidal) transition in the updated expression for the iron outflow rate in Eq. (8). The slope of the transition is controlled by the "gain" factor K. The change is schematically illustrated in the left part of Fig. 2 by the dashed-dotted line.

The differential equations for the liquid levels in the two pools can now be summarized as

\[
\begin{align*}
\frac{d^2z_{\text{in}}}{dt^2} &= \frac{s^2(m_a + m_{\text{out}}^l) + \delta_{i,j'} \left( \frac{A_e}{\rho_a} \frac{d^2z^l}{dt^2} \left( z_i^{l\prime} - z_h^{l\prime} \right) \rho_i - \tilde{m}_{\text{out}} \right)}{\rho_a A^l_E} \\
\frac{d^2z_{\text{out}}}{dt^2} &= \frac{s^2(m_a + m_{\text{out}}^l) + \delta_{i,j'} \left( \frac{A_e}{\rho_a} \frac{d^2z^l}{dt^2} \left( z_i^{l\prime} - z_h^{l\prime} \right) \rho_i - \tilde{m}_{\text{out}} \right)}{\rho_a A^l_E} \\
\frac{d^2z_{\text{in}}}{dt^2} &= \frac{d^2z_{\text{out}}}{dt^2}
\end{align*}
\]

The first term in the numerator on the right-hand-sides expresses the part of the liquid inflow to the hearth that enters into the pool in question, the second represents the cross-flow while the third considers both the change in the liquid levels caused by an expanding pool and the outflow if this is the pool being tapped. In Eqs. (9)–(12), \( \delta_{i,j'} \) is the Kronecker delta, defined as \( \delta_{i,j'} = 1 \) if \( j' = j \), else \( \delta_{i,j'} = 0 \).

The model was discretized solving the equations by an explicit scheme. After setting the geometry and model parameters and the boundary conditions, the system was run until a quasi-stationary state was reached, where the liquid levels repeated their evolution in every tap cycle.

3. Results

The mathematical model was evaluated by running it under different parameter values, observing how the performance was affected in terms of slag delay, duration of the taps and evolution of the liquid levels. To verify the findings, measurements from a reference BF were used. We apply the model to a large blast furnace with a hearth diameter of \( d = 14 \) m and a hot metal production rate of \( m_{\text{out}} = 480 \) t/h \( = 8 \) t/min, with a slag ratio of 200 kg/t, using hot metal and slag densities of \( \rho_a = 7.0 -\frac{1}{m^3} \) and \( \rho_i = 2.6 -\frac{1}{m^3} \), respectively. The assumed deadman voidage was \( \varepsilon = 0.3 \) and the two tapholes were taken to operate alternately, both being simultaneously plugged for a period of \( \Delta t_{\text{plug}} = 6 \) min.

The following basic parameter values were used initially: The two pools were quite well connected (\( \varphi_e = 2.4 -10^{-4} \) s, \( \varphi_i = 1.2 -10^{-4} \) s), the inner ends of the tapholes were assumed to be on identical levels with a fuzzy region of \( \pm 5 \) cm around the taphole, i.e., \( \Delta z_{\text{in}} = 0.1 \) m in Fig. 2. In the tap-end criterion Eq. (5), we choose \( \omega = 15 \) min, and the lowest transition points around which the iron outflow is decreased in Eq. (7) was set to \( \Delta z_{\text{max}} = 0.5 \) m. The parameters related to the outflow rates were set based on the findings of the analysis of the reference blast furnace (see the Appendix): \( \Delta t_{\text{ip}} = 15 \) min, \( \Delta t_{\text{ia}} = 5 \) min, \( \gamma_{\text{t,start}} = 0.9, \gamma_{\text{i,start}} = 0.5, \beta_{\text{it}} = 0.050 \) t/min² and \( \beta_{\text{ii}} = 0.015 \) t/min². As for the parameters affecting the transitions in Eqs. (1) and (8), we use \( C = 0.1 \) min⁻¹, \( \text{pool} = 60 \) min and \( K = 20 \) m⁻³. It should be stressed that the start times of the liquid outflows (\( t_{\text{min}} \) in Eq. (4)) are determined by the time when the taphole is opened and on the outflow order discussed in conjunction with Fig. 2. Some results of the analysis are condensed in Table 1 (uniform pools) and Table 2 (non-uniform pools).

3.1. Pools of Equal Size

3.1.1. Base Case

The first case divides the hearth into two pools of equal and fixed size, i.e., \( s_{\text{in}} = s_{\text{out}} = 0.5 \). Figure 3 illustrates the resulting evolution of the liquid levels for 500 minutes at the quasi-stationary state. As expected, the two pools show
identical liquid level patterns during the taps. The tap duration for this base case is \( t_{\text{tap}} = 130 \text{ min} \) and the slag delay is slightly negative, \( t_{\text{sd}} = -2 \text{ min} \). These findings are in general agreement with the overall behavior of the hearth of the reference furnace (see Chapter 4).

### 3.1.2. Pool Communication

The exchange of liquids between the different parts of the hearth is mainly affected by the voidage of the deadman, which is influenced by the size distribution of the deadman coke, which may vary between the core and the center.\(^{12}\) Furthermore, impermeable (clogged) zones may exist, which reduce the internal flows, particularly of slag.\(^{19}\) For iron, the lack or presence of a coke-free layer below the deadman is also an influencing factor.\(^{8}\) The effect of the connection of the iron pools was analyzed by decreasing the iron communication factor to \( \varphi_{\text{ir}} = 1.2 \times 10^{-4} \text{ s} \); this raises the iron level on the non-draining side. The results depicted in the upper panel of Fig. 4 show a longer tapping time \( (t_{\text{tap}} = 186 \text{ min}) \) and a strongly increased slag delay \( (t_{\text{sd}} = 25 \text{ min}) \); the iron level is above the taphole region at the moment when the tapping starts, yielding iron-only flow initially. Before a tap ends, the iron level in the non-draining pool is quite close to the upper boundary of the taphole region, but rises during the period when the tapholes are plugged. Even though iron is tapped first, its slow initial outflow rate (cf. Fig. 2) first elevates the iron level before it starts descending, entering the taphole region after 25 minutes. Conversely, compared to the base case, a better iron communication \( (\varphi_{\text{ir}} = 3.6 \times 10^{-4} \text{ s}) \) yielded a more negative slag delay but an unchanged tap duration. As seen in the bottom panel of

<table>
<thead>
<tr>
<th>Case</th>
<th>( \varphi_{\text{ir}} )</th>
<th>( t_{\text{tap}} ) (min)</th>
<th>( t_{\text{sd}} ) (min)</th>
<th>Figure</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic setup 1</td>
<td>( \varphi_{\text{ir}} = 1.2 \times 10^{-4} \text{ s} )</td>
<td>130</td>
<td>-2</td>
<td>3</td>
<td>Reference case</td>
</tr>
<tr>
<td>Basic setup 2</td>
<td>( \varphi_{\text{ir}} = 3.6 \times 10^{-4} \text{ s} )</td>
<td>130</td>
<td>-5</td>
<td>4</td>
<td>Strong iron pool communication</td>
</tr>
<tr>
<td>Basic setup 3</td>
<td>( \varphi_{\text{ir}} = 0.6 \times 10^{-4} \text{ s} )</td>
<td>130</td>
<td>-7</td>
<td>5</td>
<td>Poor slag pool communication</td>
</tr>
<tr>
<td>Basic setup 4</td>
<td>( \varphi_{\text{ir}} = 2.4 \times 10^{-4} \text{ s} )</td>
<td>130</td>
<td>0</td>
<td>5</td>
<td>Strong slag pool communication</td>
</tr>
<tr>
<td>( \omega = 25 \text{ min} )</td>
<td>130</td>
<td>-4</td>
<td>6</td>
<td>Different taphole levels</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2.** Tap duration, slag delay and figure number illustrating the liquid levels for the cases with uniform pools.

<table>
<thead>
<tr>
<th>Case</th>
<th>( \varphi_{\text{ir}} )</th>
<th>( t_{\text{tap}} ) (min)</th>
<th>( t_{\text{sd}} ) (min)</th>
<th>Figure</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic setup 2</td>
<td>( \varphi_{\text{ir}} = 1.2 \times 10^{-4} \text{ s} )</td>
<td>130</td>
<td>-2</td>
<td>3</td>
<td>Reference case</td>
</tr>
<tr>
<td>Basic setup 3</td>
<td>( \varphi_{\text{ir}} = 3.6 \times 10^{-4} \text{ s} )</td>
<td>130</td>
<td>-5</td>
<td>4</td>
<td>Strong iron pool communication</td>
</tr>
<tr>
<td>Basic setup 4</td>
<td>( \varphi_{\text{ir}} = 0.6 \times 10^{-4} \text{ s} )</td>
<td>130</td>
<td>-7</td>
<td>5</td>
<td>Poor slag pool communication</td>
</tr>
<tr>
<td>Basic setup 5</td>
<td>( \varphi_{\text{ir}} = 2.4 \times 10^{-4} \text{ s} )</td>
<td>130</td>
<td>0</td>
<td>5</td>
<td>Strong slag pool communication</td>
</tr>
</tbody>
</table>

Fig. 3. Liquid levels for the base case with two pools of equal size. Horizontal line depicts the level of the tapholes. Levels of the draining pool are shown by colors (green squares: Pool 1; red crosses: Pool 2), non-draining by black, while diamonds represent the period when the tapholes are plugged. Results are summarized on row 1 of Table 1.

Fig. 4. Liquid levels of pools of equal size with poor (\( \varphi_{\text{ir}} = 1.2 \times 10^{-4} \text{ s} \), top) or strong (\( \varphi_{\text{ir}} = 3.6 \times 10^{-4} \text{ s} \), bottom) iron communication. Results are reported on rows 2 & 3 of Table 1.
Fig. 4 the levels in the iron pools differ by only 0.1–0.2 m.

A similar analysis of the slag cross-flow was undertaken by halving or doubling the value of the communication factor from its base value. For a poor slag communication ($\varphi_{sl} = 0.6 \times 10^{-4}$ s) an interesting observation can be made by comparing the top panel of Fig. 5 with the results of Fig. 3: The larger height of the slag column gives rise to a higher pressure on the non-draining side, which increases the iron cross-pool flow, making the iron levels in the pools more uniform. This coupling of the liquid pools, as also noted and discussed by other authors, leads to a more negative slag delay ($\Delta t_{sd} = -7$ min) but no change in the tap duration. Negative slag delays have also been noted by other investigators (see, e.g., ref. 17, Fig. 1). An increase in the slag communication factor, in turn, result in larger differences in the iron pool levels and eliminates the slag delay so iron and slag start flowing out simultaneously since the interface in the tapping pool falls within the taphole region, as depicted in the bottom panel of Fig. 5.

3.1.3. Taphole Levels and Tap-End Condition

In opening the taphole, the path taken by the drill may vary due to the hardness of the wall material and this may change the vertical level of the inner end of the taphole. Furthermore, as the hole is opened at a certain angle against the horizontal plane (typically about 10°), already a change of half a meter in taphole length yields a level change of about 0.1 m. Changes of this magnitude may be caused by variations in the state of the coke bed in front of the taphole and its contact with the injected taphole mud. It is clear that such differences may exist between the tapholes of a large furnace, giving rise to different inner levels of the taphole.

To study this effect, the first taphole was located 0.1 m lower than the second. The top panel of Fig. 6 shows that the lower level of Taphole 1 (green horizontal line) naturally yields lower iron and slag levels in the pool, and the slag delay becomes slightly more negative in Pool 2 while iron and slag enter the taphole simultaneously in Pool 1. The results still indicate that the system is quite insensitive to small changes of the taphole levels, which cannot be avoided in the practical operation of the blast furnace.

The tap end is determined by Eq. (5), where the parameter $\omega$ reflects the effect of slag viscosity, deadman voidage and coke diameter. As these variables may vary with time and with the in-furnace state, the role of the parameter was studied by increasing its value to $\omega = 25$ min. Comparing the results in the bottom panel of Fig. 6 with those of Fig. 3, the slag level is seen to be elevated by approximately 0.6 m. Since the higher slag level affects the end level of iron through Eq. (6), the latter is lowered, resulting in a slightly more negative slag delay ($\Delta t_{sd} = -4$ min) but the tap duration is not affected.

3.2. Pools of Different Size

Simulations were also undertaken assuming symmetric and asymmetric pools of variable size. Here we thus assume that the region to be drained expands with time, which makes the initial descent of the liquid levels faster in the draining pool. The results are reported in figures and
in Table 2.

3.2.1. Symmetric Case
Here we study the case with $s_{\text{min}}^{1} = s_{\text{min}}^{2} = 0.4$, i.e., tapping pools that grow (according to the sigmoidal transition of Eq. (1)) from 40% to 60% of the cross-sectional area, while the opposite pool shows a corresponding shrinking. The variable pool size (Fig. 7) leads to a behavior where the iron level of the draining pool stays close to the taphole level during the first half of the tap, as the growth of the pool brings in iron from the adjacent pool with clearly higher iron level. The tap duration is longer than in the case with fixed pools and the slag delay somewhat more negative (row 1 of Table 2). A sensitivity analysis with respect to the pool communication factors gave results in general agreement with the corresponding analysis for the fixed-pool case, but the slag delay is shifted to lower (i.e., more negative) values. The results are summarized on rows 2–5 of Table 2.

3.2.2. Asymmetric Case
The asymmetric case is expected to shed some light on the tapping of BFs where the two draining tapholes are not symmetrically located. A non-uniform distribution of the hearth gives rise to more complex liquid level patterns. Studying a case with slightly non-uniform pools, $s_{\text{min}}^{1} = 0.4$ and $s_{\text{min}}^{2} = 0.5$, where Pool 1 spans 40...50% of the hearth and Pool 2 spans 50...60%, the two pools show differences in terms of liquid levels, tap length and slag delay (upper panel of Fig. 8): The tap duration in the smaller pool ($t_{\text{tap}}^{1} = 134$ min) is somewhat longer than in the case with uniform pools, but shorter than in the larger pool ($t_{\text{tap}}^{2} = 146$ min). The slag delay is more negative in the smaller pool ($\Delta t_{\text{sd}}^{1} = -5$ min), which is a consequence of the longer tap duration of Pool 2, which lowers the iron end level.

Finally, a very non-uniform division of the liquid pools was considered, $s_{\text{min}}^{1} = 0.2$ and $s_{\text{min}}^{2} = 0.5$, where Pool 1 spans 20...50% while Pool 2 spans 50...80% of the hearth. The lower panel of Fig. 8 shows that the liquid levels in the larger pool stays very close to the taphole during the first half of the tap, while it in the smaller pool show a wave motion, caused by the gradual increase in the outflow rate in combination with a growing pool size. The tap duration is 17 minutes longer in the large pool and the slag delay is less negative.

4. Comparison with Practical Findings
Many assumptions behind the model (cf. Chapter 2) were inspired by practical findings in a reference steel plant, where the outflow rates of iron and slag from a three-taphole blast furnace were measured. In this chapter, a brief analysis of these measurements from a period of three months, comprising more than 800 taps, is undertaken and the findings are presented and compared with the results of the liquid level model.

The Appendix presents the way in which the measured liquid outflow rates of the blast furnace were approximated by the outflow rate model of Eq. (4). In analyzing the results, level changes were occasionally seen in some of the estimated model parameters, and it was further noted that the major changes occurred when the set of tapholes in operation changed. At the BF in question, two tapholes are alternately operated for a few weeks, after which one is exchanged by the idle taphole. Only during the transition phase, all three tapholes may be operated at the same time, but also here without overlapping taps. The top panel of Fig. 9 shows the slag delay determined from the observed outflow rates of iron and slag, with vertical dashed lines indicating the approximate moments of taphole changes. The small insert depicts the location of the tapholes. (Taps for which it was difficult to uniquely determine a delay have not been depicted and thus appear as zero in the graph.)
Considering the fact that the large positive slag delays seen in the figure were almost exclusively cause by stoppages or delayed tappings, the magnitude predicted by the model must be considered to be in quite good agreement with the observations. The slag delay is also seen to show different behavior during different periods. For instance, during the first period the delays are slightly negative or zero, with a few positive delays: iron and slag enter the taphole almost simultaneously. During the second period, and particularly its central part, one taphole shows quite negative slag delays (−5 min to −15 min), while the other shows practically zero delay. The third period shows slightly zero or negative delays, except some major positive values. Also here, there are parts where the two tapholes behave very differently. Finally, the fourth period initially shows some taps with large slag delays caused by irregular operation, followed by a phase where both operating tapholes show small or negative slag delay.

As an example of a period with differences between the tapholes, the slag delay for taps 578–600 have been depicted in the bottom panel of Fig. 9. It is seen to be quite negative in one taphole, while there is no or little delay in the other except one long delay for tap #586. The reason for this high value is an interruption of tap #585, which resulted in a small (about one third of an average) iron tapping. The duration of this tap is less than an hour, while the tap that follows (#586) lasts for more than three hours. The corresponding outflow rates for eight taps (#587–594) have been plotted in Fig. 10, where the left panels that correspond to Taphole 3 (TH3) show the negative slag delay. In an attempt to explain how such taps could arise, a hearth with asymmetric and variable pools, \( s^{(1)}/g_{11}/g_{12} = 0.2 \) and \( s^{(2)}/g_{11}/g_{12} = 0.5 \) (corresponding to the last case studied in Section 3, cf. bottom panel of Fig. 8), was studied. To include some randomness in the model, fluctuations of the parameter \( \omega \) in Eq. (5) were introduced to reflect stochastic changes of the conditions in front of the taphole, which may be induced by the extent of the taphole mud mushroom and the contact of it with the coke bed,\(^{25}\) local variations in coke-bed voidage and shape of the resulting taphole mouth, etc. The parameter was expressed as

\[ \omega = (15 + 3\eta) \text{ min}; \quad t > 1000 \text{ min} \quad (13) \]

where \( \eta \) is a normally distributed random variable with zero mean and unit variance; thus, 99.7% of the values of \( \omega \) should fall within the range (15 ± 3·3) min. These variations were introduced after a quasi-stationary state had been reached. It should be stressed that all other model parameters were chosen as in the basic setup. The results, depicted in Fig. 11 for a 16-hour period holding six consecutive taps, illustrate the role of the stochastic variation on the liquid levels. The simulated tap durations and slag delays for a longer (2,500-minute) period holding 18 taps are presented in Fig. 12. Comparison of this with the results of Figs. 9 and 10 shows qualitative agreement with respect to tap duration and slag delay. Thus, non-uniform and variable drainage areas in the hearth may be a plausible explanation of the observed variations in the draining patterns.

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**Fig. 9.** Observed slag delays in the reference BF. Top: Three-month period; vertical dashed lines indicate taphole changes. Bottom: Short period where the two tapholes show different behavior.

**Fig. 10.** Normalized outflow rates for Taphole 3 (left panels) and Taphole 1 (right panels) for taps 587–594 in the reference BF. The slag delay is reported in the lower right part of each subpanel.
5. Conclusions and Future Work

This paper has presented a model of the blast furnace hearth, where mass balances for iron and slag combined with a simplified parameterized expression of the liquids outflow rates and specific conditions for detecting when the outflow of the two liquids starts and ends yield a description of the time evolution of the liquid levels. The hearth is divided into two pools, where the tapping pool may expand while the other pool shrinks during the elapse of the tap. Based on parameters estimated on measurements of the true outflow rates in a reference blast furnace, the model was applied to simulate liquid level patterns under different conditions, and some of the results were compared with practical findings. It was found that the model could reproduce some key factors of the drainage reasonably well and that it can be used in a reverse engineering approach, where hypotheses on the state of the blast furnace hearth can be tested by evaluating the model and comparing its results with available measurements. However, the present analysis is limited by considering only two liquid pools, and also by the lack of a direct verification of the results. Furthermore, the pool communication factors have been chosen by trial and error without a solid theoretical background. These issues should be addressed in future work. There are several other ways in which refinement is needed is in describing the outflow rates or iron and slag. Here, it would be natural to consider the pressure loss in front of the taphole and in the taphole. However, it is clear from the present and other investigators’ analyses that the dynamic conditions in the beginning of the taps, where the outflow rates increase, is a challenging phase to model. Another aspect that should be taken into account is the possible motion of the coke bed since a floating/sinking of the deadman strongly affects the liquid levels. Further validation of the model could be based on a deeper analysis of its interpretation of the levels in the liquid pools. Here, correlating the liquid levels with information from emf measurements or strain gauges are potential alternatives. Attention could also be focused on periods at and after taphole changes. The data described in the Appendix and briefly illustrated in Chapter 4 indicate that the system undergoes major changes at these points, and that the differences between the pools then gradually decrease. A statistical analysis of tapped quantities of iron and slag, taphole length, slag delay, etc. could be used together with the model to provide a better understanding of the complex conditions in the blast furnace hearth.

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Nomenclature

**Roman**

- \( a \): filter constant, -
- \( A \): area, \( m^2 \)
- \( C \): transition parameter in Eq. (1), \( \text{min}^{-1} \)
- \( d \): hearth diameter, m
- \( g \): gravitational acceleration, \( m/s^2 \)
- \( i \): index for phase (ir, sl), -
- \( j \): index for pool, -
- \( K \): gain coefficient in Eq. (8), \( m^{-1} \)
- \( L \): pool interface length, m
- \( m \): mass, ton
- \( p \): pressure, Pa
- \( s \): area share, -
- \( t \): time, min
- \( x \): general variable, -
- \( z \): vertical height, m

**Greek**

- \( \beta \): parameter for taphole erosion rate, \( t/\text{min}^2 \)
- \( \delta \): Kronecker delta, -
- \( \epsilon \): deadman voidage, -
- \( \eta \): stochastic variable, -
- \( \gamma \): initial outflow rate as share of inflow rate, -
- \( \theta \): angle expressing increase in outflow rate, rad
- \( \varphi \): cross-pool communication factor, s
- \( \rho \): density, \( kg/m^3 \)
- \( \sigma \): sigmoid function, defined in Eq. (1)
- \( \omega \): parameter in Eq. (5), min

**Subscripts**

- end: end point
Superscripts

(j): pool number $j$

A dot above a symbol denotes a flow rate, a hat (^) a filtered variable, and a tilde (¯) a revised value.

REFERENCES


Appendix

The liquid outflow model described in Chapter 2 was applied to analyze outflow measurements from the plant. A piecewise linear function as illustrated in Fig. 2, with a ramp-up phase, followed by a phase (often with a slower increase) was fitted to the outflow measurements after normalization, where the outflow rates were divided by the average production rate for each tap. For numerical reasons, the fourth parameter was written as the ratio of the outflow rate at the end of the tap and the mean production rate of the tap, $\gamma_{i,\text{end}}$. The value of $\beta_i$ in Eq. (4) can be readily be obtained from it by $\beta_i = m_{i,\text{end}} / (\gamma_{i,\text{end}} - \gamma_{i,\text{start}})$; $i$ is ir, sl, where $t_{\text{end}}$ is the tapping time. The parameters were obtained by minimizing the square sum of the differences between the observed outflow rates and the rates given by the piecewise linear expression Eq. (4). An example of normalized outflows for a typical tap and the approximation provided by the model (solid and dashed lines, respectively) is presented in the top panel of Fig. A1. The model is seen to be quite accurate and to approximate the measured signals reasonably well. The evolution of the model parameters of the iron outflow for a set of 800 taps are presented in the bottom panel of the figure. To remove some noise, the parameters were passed through a first-order filter $x(t) = (1-a)x(t)+ax(t-1)$, where symbols with a hat (^) denote filtered values. The parameters expressing the iron and slag outflow start times were found to fall in the ranges 4...8 min and 5...10 min, respectively, while the corresponding durations of the ramp-up phases were 10...20 min and 3...8 min. As for the outflow ratios, the analysis gave the estimates $\gamma_{\text{ir, start}} \approx 0.9$ and $\gamma_{\text{ir, end}} \approx 1.3$ for iron and $\gamma_{\text{sl, start}} \approx 0.5$ and $\gamma_{\text{sl, end}} \approx 1.4$ for slag, which justify the choice of model parameters in the analysis of Chapter 3.

![Fig. A1. Top: Example of measured normalized outflow rates of iron (blue solid line) and slag (red solid line) and piecewise approximations (dashed lines) using Eq. (5). Bottom: Parameters for the piecewise linear model describing the outflow rates of iron for 800 consecutive taps.](image-url)