Model Analysis of the Operation of the Blast Furnace Hearth with a Sitting and Floating Dead Man

Johnny BRÅNNBACKA and Henrik SAXÉN
Heat Engineering Laboratory, Åbo Akademi University, Biskopsg. 8, FIN-20500 Åbo, Finland.
E-mail: johnny.brannbacka@abo.fi, henrik.saxen@abo.fi

(Received on March 3, 2003; accepted in final form on May 11, 2003)

The phenomena in the blast furnace hearth are extremely complex and the possibilities to directly measure its internal state are practically non-existent. In order to control the process to achieve smooth operation and long campaigns, a thorough understanding of the conditions in the hearth is required. Such knowledge can be gained through mathematical modeling of the internal conditions. Since the properties of the dead man are known to considerably affect the hearth conditions, a model describing the operation of the hearth with a sitting, partially or completely floating dead man has been developed. Simulation of the tap cycle of a one-taphole blast furnace shows the effect of boundary conditions, hearth geometry, coke voidage and dead-man floating state on the evolution of the liquid levels and the slag delay. On the basis of the computed inner geometry of the hearth, the model has been applied to data from a six-year period of a Finnish blast furnace, and it has been found to accurately predict the long-term variations in the slag delay.

KEY WORDS: blast furnace hearth; tap cycle; dead man floating; slag delay.

1. Introduction

The hearth plays an important role for the operation of the blast furnace, since it is the region where the main product, pig iron, assumes its final temperature and composition. The hearth also acts as an intermediate store of metal and slag, and a sufficient volume and an undisturbed drainage are prerequisites of an efficient furnace operation. The hearth coke, (the core of) which is often called the dead man, either extends to the hearth bottom or floats partially or completely in the liquid bath, and its state is known to have a large impact on the draining conditions.

Hearth management is an important step in controlling the blast furnace, since problems in this part of the furnace often affect the operation as a whole. To ensure a stable and sustainable operation, several hearth variables should be controlled, the most important of them being the iron and slag levels and the erosion or skulling of the hearth lining.

Unfortunately, these variables cannot be measured directly during the campaign, so the operators have to rely on estimates based on indirect measurements. Mathematical models of the hearth can be used to interpret the indirect measurements, but it is important that the models have an appropriate structure for describing the phenomena.

An interesting indirect technique for estimating the voidage of the bottom part of the dead man was introduced by Desai[10] and later applied by Danloy et al.[11] By measuring the pressure in the liquid phase through an unused tap-hole an estimate of the slag level in the hearth could be made. Danloy et al. compared the tap-cycle evolutions of the estimated slag level and liquid volumes, yielding an estimate of the dead-man voidage. Drawbacks of this model are that only the total liquid level can be estimated, not iron and slag separately, and that the pressure measurement is available during short campaigns only. An on-line technique for estimating the voidage of the bottom part of the dead man was introduced by Nightingale and Tanzil[12] utilizing knowledge of the behavior of the iron and slag levels during the tap cycle to “measure” the position of the iron–slag interface. When slag starts to flow out after a period of iron-only flow in the beginning of a tap, the iron–slag interface is assumed to be at the taphole level. After this, the interface is taken to de-
send further to a certain (given or calculated) level below the taphole at the end of each tap. Under these assumptions, the voidage of the dead man can be estimated once in every tap cycle from produced and tapped quantities of iron.

According to Zulli,\textsuperscript{13} a coke-free zone at the bottom of the hearth does not influence the cyclic behavior of the liquid levels as long as its volume is constant and it does not extend above the surface of the iron phase. However, if a coke-free zone below the dead man exists, the reason must be that the dead man is (at least partially) floating, so the position of the dead man, and thus also the size of the free space below it, depends on the volume of the liquids in the hearth. From this it follows that it is likely that the volume of the free space varies and affects the liquid levels. Therefore, the methods for estimating the dead-man voidage reviewed above apply only for a hearth with a sitting dead man. This is one of the motivations behind the modeling effort presented in the present paper, where the effect of a floating dead man on the liquid levels is investigated. In particular, the implications of dead-man floating on the slag delay, \( t_{sl} \), \textit{i.e.} the time of iron-only flow in the beginning of the tap, is studied.

2. Modeling

2.1. The Tap Cycle

In blast furnaces with one taphole, the tapping of iron and slag from the hearth follows a typical cycle, schematically illustrated in Fig. 1. When the taphole is closed both iron and slag accumulate in the hearth because of the progress of reduction and smelting of iron and slag formation. In the hearth the two liquids form separate layers, the dense iron on the bottom and the light slag layer floating on top of the iron bath. The taphole is generally kept plugged for at least 20–30 min to let the injected taphole mud solidify properly. Thus, as the tapping begins the iron–slag interface, henceforth called the iron level, is usually well above the taphole, and iron flows out first while the amount of slag in the hearth still keeps on increasing. When the iron level has descended to the taphole, slag starts to flow out together with iron, and since slag is chemically more aggressive the taphole is rapidly eroded and the total outflow rate increases. As the two phases flow out simultaneously the iron level continues its descent since iron is sucked up from levels below the taphole due to the large pressure gradient formed near the taphole by the viscous slag flow.\textsuperscript{14} The cycle is completed as gas bursts out due to the declination of the slag–gas interface (called the slag level for brevity) towards the taphole, and the taphole is plugged with taphole mud.

2.2. Simplifying Assumptions

In furnaces where there are no instantaneous measurements of the tapping rates of iron and slag, some assumptions must be made to be able to simulate the tap cycle. The following simplifications are therefore introduced:

a) Iron flows out at a constant rate during the whole tap, even after the slag has started to flow out.

b) Slag starts to flow out when the iron level has descended to the taphole level. After this point slag flows out at a constant rate until the end of the tap.

c) The production rates of iron and slag are constant.

d) The hearth operates in a quasi-stationary state, \textit{i.e.} at the end of the tap cycle the amounts of iron and slag in the hearth equal the initial amounts.

The assumptions about the outflow behavior of iron and slag are motivated by results from an earlier study of measurements of instantaneous slag and iron tap rates.\textsuperscript{15} The moment at which slag starts to flow out was selected on the basis of results from both physical and mathematical modeling reported in the literature,\textsuperscript{13,14,16–18} as well as findings from statistical tests on data from a large number of tap cycles.\textsuperscript{15} Assumption d) is motivated especially in studies of the over-all behavior of the liquid levels during the tap cycle.

2.3. Sitting Dead Man

2.3.1. Basic Formulation

If the dead man is static during the tap cycle, the coupling between the changes in liquid volume and liquid levels is straightforward. The relationship is described by

\[
\frac{dV_{\text{liq}}}{dV_{\text{ir}}} = \frac{1}{\alpha \varepsilon} \tag{1}
\]

where \( dV_{\text{liq}} \) and \( dV_{\text{ir}} \) are the changes in liquid volume and surface level, respectively, while \( A \) and \( \varepsilon \) are the cross-sectional area of the hearth and the dead-man voidage on the level of the liquid surface. If the iron level is studied, \( V_{\text{ir}} \) denotes the iron volume, but if the slag level is considered the term includes the joint volume of iron and slag. If \( A \) and \( \varepsilon \) are taken to be constant in the region where the liquid surfaces move, the unsteady positions of the surfaces are

Fig. 1. Evolution of the iron and slag levels in the hearth during the tap cycle.
given by
\[
\begin{align*}
z_a(t) &= z_a(t_0) + \frac{\Delta V_a(t)}{Ae} \\
z_d(t) &= z_d(t_0) + \frac{\Delta V_d(t)}{Ae}
\end{align*}
\] (2a)
where \(\Delta V_a(t) = V_a(t) - V_a(t_0)\) and \(\Delta V_d(t) = V_d(t) - V_d(t_0)\).

2.3.2. Illustrative Examples

Figure 2 presents the tap-cycle evolution of the iron and slag levels simulated by the simplified model. The first case (solid lines) is a tap cycle simulated with typical geometry and boundary conditions for the one-taphole furnace studied further in Subsec. 3. The dead-man voidage was assumed to be \(\varepsilon = 0.35\) and the iron level at the moment when the taphole is plugged \(\Delta z_{ir}^{\text{min}} = z_{ir}^{\text{min}}-0.25\) m below the taphole; the variable \(\Delta z_{sl}^{\text{min}}\) is henceforth called the initial iron level (of the tap cycle). The calculated slag delay for this case is \(t_d = 50.9\) min (reported on first row of Table 1). In the second case (dashed lines in Fig. 2 and second and third rows of Table 1) the effect of a 20% decrease in the effective cross sectional area, \(Ae\), is simulated, while all other parameters are kept unchanged. The change in \(Ae\) can be interpreted as a decrease in dead-man voidage from 0.35 to 0.28 or a decrease in hearth diameter from 8 m to 7.16 m. The figure shows that the change has a direct effect on the amplitude of the liquid levels and that the slag delay increases. The change in \(t_d\) from 50.9 to 58.7 min is, however, surprisingly small considering the quite dramatic change in \(Ae\). The effects of some variables on the slag delay are summarized in Table 1. The first row acts as a reference case, and the later rows report the resulting slag delays after changing one variable (highlighted with bold typeface) at a time.

2.4. Floating Dead Man

2.4.1. Basic Assumptions and Formulae

If the dead man is not stationary, the relationship between volumes and liquid levels becomes far more complicated. As the dead man moves, the size of the free volume below it changes and, hence, the effective volume of the hearth is altered. The relationship between the liquid levels, liquid volumes and free volume below the dead man is given by
\[
\frac{dz_{sl}}{dV_{liq}} = \frac{1}{Ae} \left( 1 - \frac{dV_f}{dV_{liq}} \right)
\] (3)
where \(dV_f\) denotes the change in the free volume. Thus, to be able to model the motion of the liquid levels the relationship between the liquid volume in the hearth and the free volume below the dead man must be given. Therefore, the following assumptions are made:

a) The dead man moves freely up and down without hysteresis or friction against the hearth wall.

b) The force, \(F_d\), pressing down the dead man, i.e. the weight of the burden reduced by the lifting force of the gas flow and the wall friction, is independent of the vertical position of the dead man: There is no harmonic force component in \(F_d\) striving to keep the dead man at a certain position.

c) \(F_{di}\) is formed by a pressure profile \(p_d\) that has a given distribution over the hearth cross-sectional area \(A\).

d) In its submerged region the dead man has a uniform voidage in the vertical dimension.

e) At every sub-area \(dA\) of \(A\) the downward-acting pressure \((p_d)\) is balanced by the buoyancy pressure acting on the coke bed submerged in the slag and iron bath \((p_{b,ir})\) and \((p_{b,sl})\), and, if the dead man reaches the bottom of the hearth, by the supporting pressure of the hearth bottom \((p_{bh})\). The position of the dead man is derived from a force balance, as shown in Fig. 3. The buoyancy pressure acting on a submerged porous material is given by
\[
p_{b,ir} = \rho_{b,ir} g (1 - \varepsilon) h_a; \quad \text{.........(4a)}
\]
\[
p_{b,sl} = \rho_{b,sl} g (1 - \varepsilon) h_a; \quad \text{.........(4b)}
\]

---

**Table 1.** Effect of production, initial iron level, dead-man voidage, hearth diameter and tap interval on the slag delay for the case with a sitting dead man.

<table>
<thead>
<tr>
<th>Case</th>
<th>Hot Metal Production (t/d)</th>
<th>(\Delta z_{ir}^{\text{min}}) (m)</th>
<th>Dead-Man Voidage (%)</th>
<th>Hearth Diameter (m)</th>
<th>Tap Length (min)</th>
<th>Plugged Time (min)</th>
<th>Slag Delay (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3400</td>
<td>0.25</td>
<td>0.35</td>
<td>8</td>
<td>90</td>
<td>30</td>
<td>50.9</td>
</tr>
<tr>
<td>2</td>
<td>3400</td>
<td>0.25</td>
<td>0.28</td>
<td>8</td>
<td>90</td>
<td>30</td>
<td>58.7</td>
</tr>
<tr>
<td>3</td>
<td>3400</td>
<td>0.25</td>
<td>0.35</td>
<td>8</td>
<td>90</td>
<td>30</td>
<td>58.7</td>
</tr>
<tr>
<td>4</td>
<td>3600</td>
<td>0.25</td>
<td>0.35</td>
<td>8</td>
<td>90</td>
<td>30</td>
<td>53.1</td>
</tr>
<tr>
<td>5</td>
<td>3400</td>
<td>0.30</td>
<td>0.35</td>
<td>8</td>
<td>90</td>
<td>30</td>
<td>53.1</td>
</tr>
<tr>
<td>6</td>
<td>3400</td>
<td>0.20</td>
<td>0.35</td>
<td>8</td>
<td>90</td>
<td>30</td>
<td>58.7</td>
</tr>
<tr>
<td>7</td>
<td>3400</td>
<td>0.25</td>
<td>0.35</td>
<td>8</td>
<td>90</td>
<td>25</td>
<td>43.1</td>
</tr>
<tr>
<td>8</td>
<td>3400</td>
<td>0.25</td>
<td>0.35</td>
<td>8</td>
<td>90</td>
<td>35</td>
<td>56.5</td>
</tr>
</tbody>
</table>
where \( h \) is the immersion depth of the dead man in the liquid phase (slag or iron). If the downward-acting pressure profile, the iron and slag levels and the dead-man voidage are known, the vertical position of the dead-man bottom, \( z_{dm} \), can be calculated at each point of the cross-sectional area from

\[
z_{dm} = \begin{cases} 
  z_d - \frac{p_{sl}}{\rho_{sl}(1-\varepsilon)} & \text{if } 0 \leq p_{sl} \leq p_{sl}^{\max} \\
  z_d + \frac{p_{ir}}{\rho_{ir}(1-\varepsilon)} - \frac{p_{sl}}{\rho_{sl}(1-\varepsilon)} & \text{if } p_{sl}^{\max} < p_{sl} \leq p_{ir}^{\max} + p_{sl}^{\max} \\
  z_{bb} & \text{if } p_{sl} > p_{ir}^{\max} + p_{sl}^{\max}
\end{cases}
\]

where \( p_{sl}^{\max} = \rho_{sl}(1-\varepsilon)(z_{bb} - z_d) \) and \( p_{ir}^{\max} = \rho_{ir}(1-\varepsilon)(z_d - z_{bb}) \). Introducing \( A_{dm} \), the cross-sectional area of the dead man, the volumes of iron and slag in the hearth as well as the free volume can be calculated by

\[
V_s = \int_{z_d}^{z_{bb}} [A - A_{dm}(1-\varepsilon)]dz \quad \text{(6a)}
\]

\[
V_d = \int_{z_d}^{z_{bb}} [A - A_{dm}(1-\varepsilon)]dz \quad \text{(6b)}
\]

\[
V_f = \int_{z_d}^{z_{bb}} [A - A_{dm}]dz \quad \text{(6c)}
\]

Fig. 3. Forces acting on the dead man.

Fig. 4. Cross-sectional areas in the case of a floating dead man.

2.4.2. The Downward-acting Pressure

Equation (5) shows that the downward-acting pressure, \( p_{sl} \), has a strong influence on the position of the dead man. It consists of the pressure of the burden, \( p_c \), reduced by the lifting pressure of the gas flow \( \Delta p_g \) and the supporting effect of the wall, \( \Delta p_w \), i.e.,

\[
p_{sl} = p_c - \Delta p_g - \Delta p_w \quad \text{...............(7)}
\]

The burden pressure can be estimated if the (average) position of the cohesive zone and the holdups of iron and slag below the cohesive zone are known. Denoting the liquid holdup (volume fraction) by \( x \), the bulk densities of the burden and coke by \( \rho_c \) and \( \rho_c \), respectively, and the vertical positions of the cohesive zone and the stock level by \( z_c \) and \( z_{sl} \), respectively, the static pressure of the burden at the dead-man bottom is

\[
p_{sl} = \rho_c g(z_{sl} - z_c) + (\rho_c x_c + \rho_s x_s) g(z_c - z_d)
\]

\[
+ \rho_s g(z_d - z_{dm}) \quad \text{...............(8)}
\]

The lifting pressure of the gas flow can be calculated from the blast pressure (measured in the bustle main), \( p_{bl} \), and at the top gas pressure, \( p_{top} \), considering the pressure loss in the tuyere (nose)

\[
\Delta p_g = \frac{p_{bl} - p_{top} - \xi_1 \rho_{sl} w^2}{2} \quad \text{...............(9)}
\]

where \( \rho_{sl} \) is the density of the blast, \( w_1 \) is the (computed) gas velocity in the tuyere nose and \( \xi_1 = 1.1 \) is the loss factor of the outlet. The supporting effect of the wall is difficult to determine accurately; here it is roughly estimated by assuming that it reduces the downward-acting pressure by a certain fraction, \( \gamma \), i.e.,

\[
\Delta p_w = \gamma (p_c - p_{sl}) \quad \text{...............(10)}
\]

The radial distribution of \( p_{sl} \) at the bottom of the furnace is also difficult to estimate, since it is affected by the radial distributions of burden and liquid holdup, wall friction, effect of the raceways, etc. However, from dissections of quenched furnaces it is known that the dead man is likely to float higher near the wall beneath the raceway zones. Therefore, instead of attempting to rigorously estimate the radial distribution of the pressure, an overall term, \( p_{sl} \) (independent of \( r \)) is calculated from Eq. (7) and used in a simple parameterized model to describe the radial profile of the downward-acting pressure that shapes the bottom of the dead man.
where $R$ is a scaling factor, e.g., the radius of the unworn hearth at the start of the furnace’s campaign. Thus, the pressure is assumed to be constant within a central region and (for $a>0$) to decrease as the wall is approached. The expression (11) is extremely flexible, which is seen in Fig. 5 that illustrates the arising dead-man bottom profiles (in the iron phase) for some parameter values.

2.4.3. Illustrative Examples

To illustrate the effect of a floating dead man, a tap cycle with similar properties as the first example case in Subsec. 2.3.2 (solid lines in Fig. 2) was simulated. The dead-man shape was modeled by the parameters $a=190$ kPa, $r_0=2$ m, $R=4$ m and $n=2$ in Eq. (11) to qualitatively mimic the findings from hearth dissections and the hearth geometry was considered a cylinder with a diameter of 8 m and sump depth of 1.5 m. Two different floating states were simulated with $\bar{p}_d=120$ kPa (case 1) and $\bar{p}_d=100$ kPa (case 2).

The lower panel of Fig. 6 depicts the predicted evolutions of the liquid levels (case 1 with solid lines and case 2 with dashed lines). As can be seen, the slag delay in case 2 ($t_{sl}=15.1$ min) is considerably shorter than in case 1 ($t_{sl}=38.7$ min) and very much shorter than in the sitting dead-man reference case of Subsect. 2.3.2 ($t_{sl}=50.9$ min).

The liquid levels follow the general pattern illustrated in Fig. 1, but the amplitude clearly decreases with increasing dead-man floating degree. An interesting observation is that the descent rate of the iron level decreases as the level reaches the taphole even though the outflow rate is constant. The upper panel of Fig. 6 depicts the dead-man positions at the start of slag outflow for the two cases. The reason for studying the conditions at this moment is that the slag delay is mainly influenced by the difference in free volume between the moment of slag flow start and the end of the tap.

3. Simulation

Two industrial blast furnaces have been monitored and the erosion and buildup profiles of the hearths of the furnaces have been estimated from thermocouple measurements in the lining since the campaign starts. Considerable variations in the slag delay were observed in BF B, showing a strong negative correlation with changes in the volume of the hearth. In BF A no correlation between slag delay and hearth volume has been observed, even though the hearth volume has varied considerably. The measured slag delays and the estimated hearth volumes of the furnaces have been depicted in Fig. 7. The difference between the furnaces is believed to depend mainly on the floating state of the dead men: In BF B indicators show that the dead man floats during parts of the campaign, while there are no such indications in the data from BF A. In what follows, the model described in Sec. 2 is applied on data from BF B.

3.1. Simplified Model

3.1.1. Setup

A simple model of the hearth was formulated to be able
to study and illustrate the effect of different parameters on the behavior of the liquid levels and the slag delay. In the model the hearth is assumed to be cylindrical with a flat bottom. The simplified liquid flow patterns described in Subsec. 2.2 is used for modeling the mass balance of the liquids in the hearth, and the radial distribution of the downward-acting pressure is given by Eq. (11). If the dead-man bottom stays within the iron phase, it is straightforward to express its position and shape analytically and the integrals of Eq. (6) can be solved efficiently.

Before the system can be simulated, the initial liquid levels have to be pre-set. A suitable value for the initial iron level would be a one that yields a slag delay in agreement with observed values. At the blast furnaces studied in this work the tap length is approximately 90 min and the slag delay has been found to be about 60 min during periods when the dead man is presumed to sit. This observation applies for both BF A, where the dead man has been sitting during the whole campaign, and BF B during the first year after blow-in, when the hearth was unworn, but also during later periods when the hearth was clogged. A one-hour slag delay is obtained if the initial iron level is \( \Delta z_{\text{sl}} = 0.25 \) m below the taphole, varying somewhat with production rate, hearth cross-sectional area and coke voidage. As for the slag surface, its initial level cannot be measured or estimated accurately. However, the average slag–gas interface should stay above the taphole during the whole tap cycle, so its lowest position has been set at \( \Delta z_{\text{sl}} = z_{\text{sl}} - z_0 = 0.50 \) m above the taphole level in the examples that follow.

### 3.1.2. Results

Process data from two days of operation of the BF B are first used to exemplify different states of the hearth. The first day (Day 1) corresponds to a state where the hearth was eroded and the average slag delay was only 13.7 min (Arrow a in Fig. 7). Shortly after this day buildup layers started to form on the hearth wall and bottom, eventually clogging the hearth partially, yielding poor drainage and long slag delays during a period of about one year. On a later day (Day 2), taken to represent the skewed and clogged state, the slag delay was 67.1 min, and the estimated hearth volume was at its minimum during the clogged period (Arrow b in Fig. 7). The process variables required for the simulation of the two states are given in Table 2. The hearth geometry estimated by the wear model, discussed further in the next subsection, was simplified to cylindrical shape by taking averages of the hearth depths and diameters, yielding the values reported in columns four and five of Table 2. The geometrical simplifications were introduced to make the examples more transparent and easier to interpret.

On Day 2, when the hearth was severely skulling, it is very likely that the dead man was in a completely sitting state, which was also confirmed by dead-man floating indicators developed by the authors. Hence, this state was taken as a reference case for a sitting dead man. Simulation on the data for Day 2 (cf. second row of Table 2) using a dead-man voidage of \( \varepsilon = 0.35 \) yielded a slag delay in agreement with the measured value if \( \Delta z_{\text{sl}} = 0.26 \) m. Keeping this initial iron level and the voidage constant, the state on Day 1 was simulated with the variables reported on the first row of Table 2. This yielded a much longer slag delay (41.2 min) than the observed one (13.7 min). Analysis with the model showed that in order to reduce the delay to the observed value, the voidage of the dead man would have to be changed to \( \varepsilon = 0.63 \), or the initial iron level to \( \Delta z_{\text{sl}} = 0.47 \) m. The voidage change is clearly too dramatic to be a plausible explanation of the observed behavior. As for the initial level of the iron, the asymptotic behavior derived by Tanzil et al., \( \Delta z_{\text{sl}}(\Delta z_{\text{sl}} + \Delta z_{\text{ir}}) = \rho_{\text{sl}}/\rho_{\text{ir}}, \) would predict a slag-layer height of at least \( \Delta z_{\text{sl}} = 1 \) m above the taphole at the moment when the tap ends. This value seems unusually high, especially since the slag flow rate was lower during Day 1.

In order to study whether dead-man floating, preferentially at the hearth wall, could explain the changes in the slag delay, the pressure profile, \( \rho_{\text{sl}} \), was taken to decrease towards the wall by using \( a = 190 \) kPa, \( R_0 = 2 \) m, \( R = 4 \) m and \( n = 2 \) in Eq. (11). Again starting by studying data for Day 2 and adjusting the overall value of the downward-acting pressure, it was found that \( \rho_{\text{sl}} = 110 \) kPa gave a dead man that barely floated near the hearth wall at maximum buoyancy pressure in the tap cycle. However, the extent of the floating was small and had no notable effect on the slag delay. With these settings, using the same \( \Delta z_{\text{sl}} = 0.63 \) m and \( \varepsilon < 0.63 \) as in the sitting dead-man case, the resulting slag delays of Day 1 and Day 2 were 16.8 min and 67.0 min, respectively. Thus, the large changes in the observed slag delay between the two states can be almost perfectly explained by the variation in the dead-man floating degree, caused by the hearth sidewall and bottom erosion and skulling alone. In the upper panel of Fig. 8 the dead-man positions at slag outflow start for the two simulated cases are depicted, while the transient behavior of the liquid levels is shown in the lower panel. Finally, it should be noted that the effect of changes in the gas pressure drop (cf. Eqs. (7) and (9)) was neglected in this simplified example to show the isolated effect of the hearth geometry on the dead-man floating state and slag delay. Had the observed changes in \( \Delta p_{\text{sl}} \) been included, the difference in floating states and slag delays between the two days would have been even larger.

### 3.2. Detailed Model

The examples in the previous subsection demonstrated that even a grossly simplified model that considers the ef-

---

**Table 2.** Variables for the two states simulated with the simplified model.

<table>
<thead>
<tr>
<th>Date</th>
<th>Hot Metal Production (t/d)</th>
<th>Slag Delay (min)</th>
<th>Hearth depth* (m)</th>
<th>Hearth diameter* (m)</th>
<th>Tap Length (min)</th>
<th>Plugged Time (min)</th>
<th>Slag Delay (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>3570</td>
<td>183</td>
<td>1.67</td>
<td>8.21</td>
<td>74.7</td>
<td>32.1</td>
<td>13.7</td>
</tr>
<tr>
<td>Day 2</td>
<td>3590</td>
<td>195</td>
<td>1.14</td>
<td>7.19</td>
<td>99.1</td>
<td>32.9</td>
<td>67.1</td>
</tr>
</tbody>
</table>

* Approximated from a more complex geometry (cf. Fig. 9) estimated by the wear model.
Since the wear model monitoring the hearth geometry does not require a symmetric (or cylindrical) geometry.

Effect of a floating dead man was able to reproduce the effect of changes of the hearth geometry on the slag delay between two extreme states. It is therefore logical to study whether the model would be able to predict changes in the slag delay during longer time periods.

3.2.1. Setup

The model of a floating dead man outlined in Subsec. 2.4 does not require a symmetric (or cylindrical) geometry. Since the wear model monitoring the hearth geometry produces a number of two-dimensional profiles of the hearth at different angles relative to the taphole, the corresponding sectors, as illustrated in Fig. 9, can be used in Eqs. (5) and (6) to calculate the cross-sectional areas ($A$ and $A_{\text{dm}}$) on different vertical levels. For the radial distribution of $p_a$, Eq. (11) was used with $a=90$ kPa, while the values of $\tilde{e}$, $\Delta_{\text{min}}$, $\Delta_{\text{max}}$, $r_0$, $R$ and $n$ were chosen exactly as in the last paragraph of Subsec. 3.1.2. The value of $a$ was altered from the simplified case, since the hearth bottom erodes to an elephant-foot shape during the campaign21 (cf. the left part of Fig. 9). The overall downward-acting pressure in the central part, $p_{\text{dm}}$ was calculated from Eqs. (7)-(10). For the sake of simplicity and in lack of more detailed information, the position of the cohesive zone and the liquid holdups were assumed to be constant throughout the studied time period, while the lifting pressure of the gas flow was estimated from the blast and top pressure measurements using Eq. (9) with a constant gas velocity of $v_w=250$ m/s in the tuyere nose. The wall friction was considered by $\gamma=0.1$ in Eq. (10). Measured values for the tap length, taphole plugged time, production rate and slag volume were used in the simulation. However, these signals were first passed through a median filter to remove outliers, followed by averaging to produce daily values.

3.2.2. Results

A number of different cohesive zone positions and liquid holdups within reasonable bounds were tested in an effort to make the simulated results match the observed slag delay of the campaign. Several of the cases gave an excellent fit of the slag delay throughout the six-year period. The top panel of Fig. 10 illustrates, the measured (dotted line) and predicted (solid line) slag delays for a case where the cohesive zone was taken to be 12 m below the stock level using liquid holdups of $x_{\text{s}}=0.02$ and $x_{\text{sl}}=0.04$. The model has clearly captured most of the changes in slag delay. For the purpose of comparison, an alternative case was simulated by the model with unchanged parameter values but applying a sufficiently high pressure $p_{\text{dm}}$ to make the dead man sit throughout the campaign. As the top panel of Fig. 11 clearly illustrates, only the case with a partially floating dead man (solid line) provides an appropriate description during time periods of short slag delay. In the lower panel of the figure the free volume below the floating dead man at the slag flow start has been depicted; the variable is a measure of the floating degree of the dead man, and it is seen to correlate very strongly with the difference in slag delay between the floating and the sitting states.

4. Discussion

In an earlier analysis of data from BF B it was found that the slag delay varied dramatically during the campaign and that it was strongly negatively correlated with the hearth volume21,22 estimated by a wear model. Since changes in hearth-coke voidage or other parameters of the model were unable to explain the radical fluctuations in the slag delay, the effect of dead-man floating was studied with the model. In order to make it possible to simulate partial floating of
the dead man, the radial distribution of the pressure of the burden was modeled by a simple parametric expression. The analysis revealed that dramatic changes in the slag delay can be easily explained by transitions between partially floating and sitting dead-man states. Applied on day averages of process data from the BF B the model was found to provide an astonishingly accurate description of the slag delay. It should be pointed out that a model formulation with a partially floating dead man was needed to produce a realistic evolution of the liquid levels during the tap cycle. Only one parameter, i.e. the height of the cohesive zone, was used to tune the model, and the value of this parameter was selected once for all, and was kept constant after this in the simulations. The results are relatively insensitive to changes in the model parameters in Eq. (11), shaping the dead-man bottle; the parameter values can be varied quite freely and a fit of the slag delay similar to the one presented in Fig. 10 can be obtained simply by adjusting the value of \( \bar{p}_d \). A consequence of this robustness is, naturally, that it is not possible to use the model for identification of the shape of the dead-man bottom from process data. However, as demonstrated in Subsec. 3.2, the (change in) free volume can be estimated because of its intimate relation with the slag delay. The model thus provides a measure of the extent of the coke-free region, the important role of which on iron flow and hearth refractory wear has been stressed by several investigators.

5. Conclusions and Future Prospects

The behavior of blast furnace hearth has been studied by a model that considers the tap-cycle evolution of the liquid iron and slag content in the hearth in a simplified but yet realistic way. The model has proven to be a powerful tool for throwing light on the behavior of the liquid levels in the hearth. It can be used both in “what-if” analysis for tap planning and to interpret observed measurements in terms of internal conditions, e.g. the floating state of the dead man. In particular, the model has been successful in explaining the mechanism behind the observed interdependence between the long-term variations in hearth refractory erosion and slag delay, i.e. the time of iron-only flow in the beginning of the tap. A large number of issues still remain unexplored. Future work will be focused on relaxing some of the simplifying assumptions made in modeling the material balances of the hearth. For instance the possibilities to model the residual amounts of iron and slag in the hearth on the basis of experimental results reported in the literature \(^{13,28,29}\) will be studied. Attempts will also be made to improve the fit between simulated and observed slag delays by estimating model parameters, such as dead-man voidage or pressure of the burden column. Furthermore, the dead-man floating model will be used in a more detailed study of instantaneous liquid level tracking. \(^{15,22,23}\) Estimated dead-man floating degrees will also be compared with the floating indices developed in earlier work.\(^{21}\)

Acknowledgements

We express our gratitude to Rautaruukki Steel in Raah, Finland, for making blast furnace data available. Financial support from Rautaruukki, the National Technology Agency of Finland (Tekes) and the Graduate School in Chemical Engineering is also gratefully acknowledged.

Nomenclature

\[ a : \text{Parameter, Eq. (11)} \]  
\[ A : \text{Cross-sectional area} \]  
\[ g : \text{Acceleration of gravity} \]  
\[ h : \text{Immersion depth of dead man} \]  
\[ n : \text{Parameter, Eq. (11)} \]  
\[ p : \text{Pressure} \]  
\[ r : \text{Radius} \]  
\[ R : \text{Parameter, Eq. (11)} \]  
\[ t : \text{Time} \]  
\[ V : \text{Volume} \]  
\[ w : \text{Velocity} \]  
\[ x : \text{Liquid holdup} \]  
\[ z : \text{Vertical level} \]

Greek

\[ \Delta : \text{Difference operator} \]  
\[ \varepsilon : \text{Coke bed voidage} \]  
\[ \zeta : \text{Loss factor} \]  
\[ \gamma : \text{Friction parameter, Eq. (10)} \]  
\[ \rho : \text{Density} \]

Subscripts

\[ 0 : \text{Initial/reference state} \]  
\[ b : \text{Buoyancy} \]  
\[ bl : \text{Blast} \]  
\[ c : \text{Coke} \]  
\[ cz : \text{Cohesive zone} \]  
\[ d : \text{Downward} \]  
\[ dm : \text{Dead man} \]  
\[ fr : \text{Free} \]  
\[ g : \text{Gas} \]
hb: Hearth bottom
ir: Iron
liq: Liquid
s: Solid/burden
sl: Slag
t: Tuyere
th: Taphole
top: Top/stockline
w: Wall

Superscripts
max: Maximum
min: Minimum
A bar above a symbol denotes an overall value.

REFERENCES