Indicators of the Internal State of the Blast Furnace Hearth

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The hearth is a crucial region of the blast furnace, since the life of its refractory may be decisive for the campaign length of the furnace. Excessive growth of skull on the hearth wall and bottom, in turn, reduces the inner volume of the hearth, causes drainage and other problems that limit productivity, and has a negative effect on hot metal temperature and chemistry. A set of indicators that reflect the internal state of the hearth has been developed. The motivation for the indicators is outlined and their application to hearth state detection is illustrated with several examples from the operation of two Finnish blast furnaces.

KEY WORDS: blast furnace hearth; dead man state; erosion and skulling; slag delay.

1. Introduction

In the operation of the ironmaking blast furnace, the management of the furnace hearth is crucial for several reasons. The state of the hearth lining is important in that erosion may limit the length of the campaign of the furnace. On the other hand, an excessive growth of skull on the hearth wall and bottom reduces the effective hearth volume and thus the possibilities to maintain a high production rate, and, furthermore, disturbs the internal flow distribution of the liquids. The internal state of the coke bed, the core of which is usually referred to as the dead man, also plays an important role for the flow conditions, hot metal composition and temperature.

Changes in the state of the hearth occur more or less frequently in blast furnaces. Some changes are clearly triggered by major disturbances, such as stoppages or large accretions that peel off the walls and descend into the hearth, while in some cases the ultimate reason for the changes can never be determined. The changes can be comparatively rapid or may evolve more gradually. Unfortunately, it is extremely difficult, if not impossible, to carry out direct measurements of the internal state of the hearth of operating furnaces. Results from quenched and dissected furnaces have shed light on the conditions that prevailed prior to blow-out, but part of the information obtained through dissections is already obsolete, because of the considerable progress in the operation of the blast furnace (e.g., increased productivity and reduced reductant rates) experienced during the last few decades. In order to prevent a gradual deterioration of the state, and to compensate for observed disturbances, timely and appropriate control actions must be taken. The measures to be taken have to be based on reasonable estimates of the state of the blast furnace hearth, since the effects of control actions may vary from state to state. If, for instance, the hearth is impermeable, a production increase may lead to problems with residual metal and slag in the hearth, while—on the other hand—a bypass channel for the hot metal around the dead man may cause high erosion rates of the lining.

To be able to understand and detect changes in the internal state of the hearth, indirect measurements in combination with mathematical modeling can be utilized. Heat transfer models based on thermocouple readings in the lining can be used as a source of information. Since the dead man is known to strongly affect the flow conditions in the hearth, information can also be extracted from tap variables. Furthermore, a possible vertical motion of the hearth coke induced by the liquid bath may be observed as changes in the gas pressure drop over the furnace and in the burden descent rate. A partial floating of the coke bed under the raceway, which has been reported by several investigators, often results in the formation of an annular coke-free region at the hearth corners, where high hot metal velocities develop. This, in turn, usually leads to an elephant-foot (or mushroom) shaped lining erosion that can be detected by heat transfer models.

This work presents an array of methods that can be utilized to give an overall picture of the state of the hearth in operating blast furnaces. Special emphasis is put on methods that provide a quantification of the observed states. After a presentation of the indicators, they are illustrated on data from the two blast furnaces of Rautaruukki in Raase, Finland. Correlation with other process variables is used to verify the findings. It is demonstrated that the methods are able to track both medium-term (on a weekly basis) and long-term (on a monthly basis) changes in the state of the furnace hearths. Finally, some suggestions for future development of the methods will be given.
2. Indicators of the Hearth State

2.1. Lining Wear and Skulling

A model estimating the residual lining and the thickness of the skull layer on the hearth wall and bottom has been developed. The routine determines the location of the 150°C-isotherm that gives the best match between measured and calculated temperatures for a set of two-dimensional vertical cross-sections of the hearth (Fig. 1), aggregating the results into a three-dimensional representation of the internal profile, as shown in Fig. 2. The model describes the state of the lining and its results can be used as a basis for decisions on control and maintenance actions, e.g., whether a relining or injection of Ti-bearing materials to form protective skull on the hearth lining should be scheduled to avoid a breakout, or if a drop in hot metal production is necessary to avoid excessive hot metal velocities. By examining the evolution of the 3-D representation, it is possible to follow the progress of the erosion and skulling in time. However, when the results of the model are correlated with other process data, it may be more useful to study the evolution of quantities such as the available hearth volume, calculated on the basis of the model’s results (cf. Sec. 3).

2.2. The Internal State of the Hearth Coke

In spite of its name, the dead man, i.e., the core of the hearth coke, is known to play an important role for the operation of the blast furnace. Its shape and permeability influence the hot metal and slag velocities and flow patterns in the hearth, and, therefore, also affect the erosion or formation of skull and the drainage of the two liquid phases. Heat and mass transfer between the slag and iron phases are also affected by the dead man state. Furthermore, the dead man may also have an impact on the conditions in the upper part of the furnace through its possible vertical motion along with changes in the levels of liquids in the hearth. In the following, some indicators of the state of the hearth coke are presented.

2.2.1. Slag Delay and Hearth Coke Voidage

A simple but extremely informative variable that reflects the internal state of the hearth is the slag delay, $t_{\text{slag}}$, i.e., the time that elapses after the tap is started until slag enters the runner. The delay, which is roughly a function of the (extreme) levels of the iron–slag interface and the taphole, as indicated in Fig. 3, is an especially useful variable in furnaces with one taphole, where the liquid levels vary more.

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Fig. 1. Schematic illustration of the erosion model. a) Finite element mesh, estimated lines and location of the thermocouples (●) for a two-dimensional sub-task. b) Aggregation of two-dimensional results into a three-dimensional representation (cf. Fig. 2).

Fig. 2. Three-dimensional representation of the internal profile of the hearth. The dark bar indicates the location of the taphole.

Fig. 3. Extreme vertical positions of iron–slag interface with respect to the taphole level as main factors affecting the slag delay. The darker liquid is “fresh iron” produced since the taphole was plugged.
drastically. In general, an increase in the slag delay indicates emerging drainage problems, but the factors affecting it are numerous. A long slag delay for a single tap may simply arise because of a long interval between two taps. If, on the other hand, easy flow paths are available for the hot metal in the beginning of the tap, they will reduce the time required for the iron–slag interface to descend to the tapping hole and, thus, also reduce the slag delay. In practice, the tapping rates of metal and slag are not constant, but change during the tap cycle, so it is generally advisable to base the analysis on a sufficient number of observations and to pass the data through an appropriate filter to remove noise of high frequency.

A method for interpreting the slag delay in terms of hearth coke voidage, ε, has been presented by Nightingale and Tanzil. In the model, it is assumed that the production and tap rates of iron as well as the minimum level of the iron–slag interface are known. This gives a set of equations that can be solved for with respect to the unknown coke bed porosity. Because of uncertainties in the assumptions applied in the model, in addition to measurement noise, the resulting estimates have to be filtered considerably, but after this procedure the variable may reveal interesting features of the coke bed. However, a problem in interpreting the results is that a skulking of the hearth walls close to the tapping hole has an identical effect as a decrease in the internal coke bed porosity, since the vertical level of the iron–slag interface depends on the cross-section area available for liquid flow. Another complication is that even a partial floating of the dead man significantly affects the liquid levels and thus also the estimated voidage.

2.2.2. Hot Metal Carbon Content or Its Deviation from Equilibrium

The hot metal dribbling into the hearth is not carbon-saturated, and during its passage through the hearth it receives carbon from the coke and from the carbon-containing lining material. Because the contact surface between iron and the coke bed is much larger than that between iron and the carbon lining, the carbonization will primarily take place in the dead man. If there is a bypass for the hot metal, e.g., around the dead man, the metal will receive less carbon from the hearth coke. The hot metal carbon content, or its deviation from equilibrium, can therefore be used as an indicator of the dead man state.

2.2.3. Tap-internal Evolution of Hot Metal Composition

At some blast furnaces multiple observations of hot metal components are available for each tap; in Rautaruukki the hot metal is tapped into ladles (typically 2–5 for each tap), and certain variables, such as the silicon and the sulfur content, are measured for each ladle. This makes it possible to follow the tap-internal evolution of the composition, which may reflect the state of the hearth. In order to be able to detect changes in the tap-internal trends, the ladle-wise composition, \( x_i(k) \), where \( k \) denotes the tap number and \( i = 1, \ldots, N \) is the ladle number in the tap, is first expressed as a relative deviation from the average value of the tap,

\[
\xi(k) = x_i(k) - \overline{x}(k) \quad \text{with} \quad \overline{x}(k) = \frac{1}{N(k)} \sum_{j=1}^{N(k)} x_j(k) \quad \text{...(1)}
\]

The problem that \( N \) varies from tap to tap can be tackled by depicting \( \xi \) against a normalized tap-cycle time, \( \tau \in (0, 1) \), e.g., distributing the ladles uniformly

\[
\tau_i(k) = \frac{i}{N(k)+1} \quad \text{...(2)}
\]

yielding the dashed line for the example in Fig. 4, and the evolution of the approximation can be followed in time. As demonstrated in the next section, special features of such a model, e.g., the location of its maximum (if \( a_1 < 0 \) with respect to normalized tap-cycle time,

\[
\tau_{\max} = \text{min}[\text{max}(0, -a_2/(2a_1)), 1] \quad \text{...(4)}
\]

may be used as an index characterizing the hearth conditions.

2.2.4. Pressure Drop and Burden Descent Rate

Floating of the dead man significantly influences the liquid levels and the hot metal velocities in the hearth. If the dead man floats, the fluctuation of the liquid levels during the tap cycle will be damped, which will affect the slag delay considerably. It also concentrates the metal flow to coke-free regions, where lining erosion may follow. The vertical motion of the dead man also influences the operation of the upper part of the furnace. When the dead man moves upwards it may deform the raceways and possibly also the clearance for coke flow in the active coke zone (cf. Sec. 3.2 of Ref. 1), which affects not only gas distribution and permeability but also burden descent; it is a well-established fact that an over-filling of the hearth slows down the driving rate.

The gas pressure drop and the burden descent rate are, however, affected by a large number of other process variables and disturbances, such as changes in blast volume and
burden distribution, hot stove shifting, hangings and slips. To filter out such effects, the dead man motion must be studied over longer periods of time (e.g., several weeks), after removing possible “outliers”, such as dramatic changes in the pressure drop caused by blast reductions and hot stove shifts. By interpolation, the values of the variables at a number of discrete points uniformly distributed in normalized tap-cycle time, \( \tau \in (0, 1) \), similar to that used in the previous subsection in the study of the tap-internal changes in composition, can be used to compute averages. Figure 5 schematically depicts the evolution of the gas pressure drop and the burden descent rate during the tap cycle in a furnace with a (partially) floating dead man.

\[
F = \Delta p(\tau) - \Delta p(0) 
\]

will in what follows be used to track changes in the vertical motion of the dead man.

2.2.5. Electromotive Force

Today it is customary to attach electrodes to the shell of the blast furnace at the tuyere level and below the taphole to measure an electromotive force (emf) that provides indirect information about the instantaneous levels of molten materials in the furnace hearth. In the furnaces studied in this work, the emf signals have been found to correlate astonishingly well with the iron levels calculated by a balance-based model, which estimates the instantaneous production rate from elemental balances and the tapping rate from level measurements in the iron ladles. However, because of the requirement that the instantaneous outflow rates be measured, it is not possible to apply the model at furnaces where such measurements are lacking; in such cases the emf is a useful tool for on-line tracking of the liquid levels on a tap-to-tap basis. Since the emphasis of the present study is to track slower changes in the internal state of the hearth, the use of emf will not be discussed in what follows.

3. Illustration of the Indicators

In this section, the indicators presented above will be applied to study the hearth state of the two blast furnaces of Rautaruukki in Raase, Finland, tracking changes on both a long-term (monthly to yearly) and a medium-term (weekly to monthly) basis. As noted in an earlier report of the research activities, the two hearths perform differently; BF1, relined in August 1995, has throughout its campaign experienced little erosion of the hearth lining, while BF2, relined in May 1996, has a more eroded hearth which is generally well drained. Figure 6 shows the increase in the volume of the lower part of the hearth of the two furnaces, estimated by the erosion model on day-averages of the lining temperatures, from October 16, 1995, to October 22, 2000. Clearly, the hearth of BF2 started to erode steadily almost immediately after blow-in and continued to do so during the first two years of the campaign; similar behavior has been reported for other blast furnaces. In BF1, excluding the initial phase, the erosion was very slow during the first two years of operation, partly caused by a strong cooling of the hearth bottom and walls. The figure also shows that the inner volume during the later stages of the period varies considerably less in BF2 than in BF1, where large spikes occasionally occur. Obviously, the skull layer in BF1 melts as the result of changes in the internal flow conditions, but is rebuilt in a few weeks. Some of these changes seem to be triggered by the increase in the coke rate prior to stoppages, while the reason for the other ones remains an open issue for further research. The differences in the operation of the hearths can also be studied in Fig. 7, where the tap-cycle trend exhibited by the gas pressure-drop evolution has been depicted for two periods in 1997 (January and December). While the pressure drop stays almost constant in BF1, a clear cyclic variation emerges during the period in BF2.
agreement with earlier findings,7) it is, therefore, likely that the hearth coke in BF1 is stagnant and extends to the hearth bottom, while it in BF2 started to float, at least partially, during the second year after blow-in. In accordance with operator know-how, the lower over-all pressure drop in the upper part of BF1 also indicates that the hearth is less permeable. The reason for this is not fully understood, but a possible explanation is that an impermeable hearth yields a non-uniform gas distribution (and possible channeling) in the upper furnace, which is accompanied by lower gas utilization and hot metal production rate.

These findings are strongly supported by the evidence shown in Fig. 8, which illustrates the changes in hearth volume and filtered values (denoted by primes in what follows) of the slag delays; tap-wise slag delays were passed through a first-order filter

$$i_{\text{slag}}'(k+1) = \alpha i_{\text{slag}}'(k) + (1-\alpha) i_{\text{slag}}(k+1) \quad \cdots \quad (6)$$

with a filter constant of $\alpha = 0.99$, corresponding to a time constant of about 8 days. In BF1 the impermeable hearth is seen to yield a long slag delay with practically no correlation with the volume. In BF2 a strong negative correlation is observed; along with the progress of the erosion, the slag delay decreases. The striking coupling between the two variables during the second half of the period can be further studied in Fig. 9, where the change in the hearth volume (dashed line) and the slag delay (solid line) have been depicted for a 350-day period. Considering the delaying action of the filter applied on the latter variable, the conclusion is drawn that fluctuations in the cross-section area available for liquid flow on the taphole level (cf. Subsec. 2.2.1) will lead to growth or melting of skull in the lower parts of the hearth. This is supported by the strong negative correlation between the hearth volume and the taphole length depicted by dashed-dotted lines in Fig. 9. Shibata et al.10) have pointed out that the most efficient method for restraining circumferential iron flow is to increase the taphole length. It is also interesting to note that similar cyclic variations in the lining thermocouples have been reported by other investigators.14,19) If the single reason for the observed fluctuations in the slag delay would be changes in the average hearth coke voidage, the method proposed by BHP12,14) would propose a voidage change of about $\Delta e = -0.15$ in the Rautaruukki furnaces to explain the observed increase in the slag delay from 20 to 50 min; this voidage change must be deemed very large. It is, therefore, more likely that the dead man floats when the lining is in its eroded state, or that the iron–slag interface is drained to a lower level, both of which are known to have a considerable effect on the slag delay.16)

The two-dimensional internal profiles corresponding to a maximum and a minimum in the hearth volume, indicated by arrows in Fig. 9, have been depicted in Fig. 10, where a mushroom-shaped erosion20) and the occurrence of an annular (most likely coke-free) passage for iron flow can be noted. The figure shows that a skull layer is formed both at the periphery and in the central parts of the hearth, but the former layer is formed first. Also these findings support the theory that the maxima of the hearth volume (e.g., at $t=1250\, \text{d}$, March 14, 1999) correspond to a state with a float-
ing dead man, while the dead man sits on the bottom of the hearth center at the minima (e.g., \( t = 1282 \) d, April 15, 1999).

As indicated in Fig. 8, the inner volume of the hearth of BF1 also shows large changes, but these are not felt in the slag delay. A probable reason for this is that in a sitting, or at least much less porous, state of the dead man the over-all effect of erosion of the hearth is small, as long as the buoyancy force exerted by the liquids is insufficient to lift the coke column. The conditions in the peripheral part of the hearths play an important role\(^{10,19}\) in the cyclic changes in the hearth volumes of the two furnaces. It was also noted that the slag delay under certain periods in BF2 correlated quite well with the hot metal carbon content. Figure 11 shows the two variables, both filtered equally, for a period of almost one year. In agreement with the findings of Nightingale et al.\(^{14}\), an increase in the slag delay (i.e., a decrease in the average coke voidage at the taphole) implies a growing impediment for the flow of iron, and thus enhanced carbonization.

Finally, the period where the dead man of BF2 started to float is examined in more detail with respect to the composition of the hot metal. Attention is focused on the performance of the hearths during the period between February 1997 and January 1998. The small upper curves in Fig. 12 show the approximation of the tap-internal trend exhibited by the hot metal silicon content, as approximated by the quadratic model of Eq. (3), together with the increase in hearth volume (dashed lines) and the dead-man floating index (dashed-dotted lines, Eq. (5)), scaled by a factor of ten. The tap-internal trend in BF1 (upper figure) remains practically unaltered throughout the time period and the float index also stays close to zero. In BF2 (lower figure), the tap-internal trend undergoes an obvious gradual transition; from showing a clear maximum (at \( t = 0.4 \)) the silicon content assumes a decreasing trend. The evolution of the dead-man floating index goes hand in hand with the other variables; a possible lower limit for floating could (subjectively) be set at \( F = 1 \) kPa.

Figure 13 illustrates with solid
lines how the time of the location of the maximum of the quadratic approximation, Eq. (4), estimated recursively on all taps (of more than one ladle),\textsuperscript{21)} varies within the normalized tap interval $t \in (0, 1)$ during the period. Sudden increases in the hearth volume and the floating index are seen to cause a shifting of the tap-cycle maximum to $t_{\text{max}}$ (see Fig. 12, e.g., at $t=610$ d and 665 d). If the silicon content of iron entering the hearth is assumed to vary periodically along with the tap cycle,\textsuperscript{22)} and the mixing of the iron “layers” is incomplete,\textsuperscript{11)} the permeable hearth of BF2 must “transform” an oscillation into a decreasing trend. There are two possible explanations for this, schematically depicted in Fig. 14, partly based on results from CFD simula-

tions. One explanation is that an increased hearth-coke voidage lowers the level to which the iron–slag interface is drained at the end of the tap (left part of the figure). The draining of iron during the tap does not, by contrast to the evolution for partially choked hearth (depicted in the right part of the figure) proceed as first-in-first-out for the iron “layers”, but instead mixes iron from the regions below and above the taphole. The other, equally plausible, explanation is that the furnace enters a state with a floating dead man that suppresses iron from the region below the taphole along with its descent during the tap, or where the outflow “order” is fundamentally altered by creating a passage for the iron flow below the dead man.\textsuperscript{10)} Thus, a sequence of ladles with decreasing silicon content is created. The effect of the flow conditions on the tap-internal evolution is illustrated schematically in the lower graphs of Fig. 14.

4. Conclusions

A set of indicators for tracking the internal state of the blast furnace hearth has been developed and illustrated on data from two Finnish blast furnaces, where the hearths show very different behavior. It has been demonstrated that the indicators can reveal fundamental changes in the state of the hearth, such as the onset of floating of the dead man. The effect of the hearth state on the outflow order of accumulated iron has also been discussed. Even though the indicators already provide valuable information about the state on-line, it is expected that future work, including theoretical analysis by CFD modeling, will bring about a deeper understanding of the phenomena that govern the performance of the blast furnace hearth region. The possibilities to further quantify the results of the models in order to facilitate their use to standardize control actions relating to the hearth performance will also be studied.

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Nomenclature

\begin{itemize}
  \item $a$: Parameter in Eq. (3) (\text{–})
  \item $C$: Hot metal carbon content (\%)
  \item emf: Electromotive force (mV)
  \item $F$: Dead-man floating index (kPa)
  \item $k$: Tap number (\text{–})
  \item $l$: Taphole length (m)
  \item $N$: Number of ladles in a tap (\text{–})
  \item $p$: Gas pressure (kPa)
  \item $r$: Radial coordinate (m)
  \item $Si$: Hot metal silicon content (\%)
  \item $t$: Time (min, d)
  \item $V$: Hearth volume (m$^3$)
  \item $x$: Chemical composition of hot metal (\%)
  \item $z$: Vertical coordinate (m)
\end{itemize}

Greek letters

\begin{itemize}
  \item $\alpha$: Filter constant in linear first-order filter (\text{–})
  \item $\Delta$: Difference operator (\text{–})
  \item $\epsilon$: Hearth coke voidage (\text{–})
\end{itemize}
\( \xi \): Deviation from mean value (\%)

\( \tau \): Normalized tap-cycle time (\(\sim\))

Subscripts

\( i \): Ladle number in a tap

\( \text{max} \): Maximum value

\( \text{min} \): Minimum value

\( o \): Taphole opened

\( \text{slag} \): Slag (entrance)

\( \text{hole} \): Taphole

Other notations

A bar above a symbol denotes an arithmetic mean value, a hat (\(^\wedge\)) denotes an estimate, and a prime on a symbol a filtered value (cf. Eq. (6)).

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