Model of the State of the Blast Furnace Hearth

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A model for estimation of erosion and skull profiles of the blast furnace hearth is presented. The model, which is based on thermocouple measurements in the hearth bottom and wall lining, estimates the most severe erosion of the lining experienced during the campaign and also the present thickness of the skull material. The model is illustrated on process data from two Finnish blast furnaces. Complementary measurements and calculations are used to verify the results. Based on the findings, conclusions are drawn about the internal state of the blast furnace hearth, for instance, whether the dead man floats or sits at the bottom. Finally, some suggestions on how to control the state of the furnace hearth are given.

KEY WORDS: erosion and skull profiles; blast furnace hearth; dead man.

1. Introduction

For the economic operation of the ironmaking blast furnace (Fig. 1), it is important to ensure a long campaign life without expensive and time-consuming relinings. Of special importance is the blast furnace hearth, which cannot be relined without extensive effort and a temporary shutdown of production. It is therefore important to carefully monitor the condition of the hearth lining during the campaign and to take appropriate countermeasures if the lining is severely degraded. Due to hostile conditions in the hearth, no direct measurements of the remaining hearth lining thickness are possible, so use has to be made of indirect measurements, such as thermocouple readings.

A proper function of the hearth is also important for the overall operation of the furnace, in terms of hot metal quality, production rate, tapping management, *etc.* To be able to take measures to maintain a stable operation of the blast furnace hearth it is necessary to get indications of the prevailing state of it. The solidification and melting of build-up material on the hearth lining depend strongly on the flow conditions in the hearth, so by monitoring the state of skulling it is also possible to detect changes in the internal flow patterns. Heat transfer models are commonly used to monitor the erosion of the blast furnace hearth and the build-up of skull on the hearth walls.^{1–3)}

The results from such models have also been correlated against other process variables and have been used to monitor the state of the hearth. Rex *et al.*⁴⁾ calculated an effective hearth liquid volume (EHLV) from the erosion calculations and found that it correlated with the residual amount of liquids in the hearth after tapping. Venturini *et al.*⁵⁾ explained transitions in measured temperatures with the change in the permeability of a ring-shaped zone at the

hearth bottom. The slag ratio showed a positive correlation with the hearth bottom temperature during this transient state. Nightingale *et al.*⁶⁾ estimated the voidage of the hearth coke from tap data, and the voidage was found to correlate with the hearth plug temperature in the case of a

Fig. 1. The ironmaking blast furnace process and the hearth region studied in this work.

sitting dead man. Hood⁷⁾ reported on the use of the skull thickness to monitor the hearth lining and to take control actions against erosion.

To be able to estimate the state of the hearth, a model for calculating the remaining sound lining and the amount of skull on the bottom and wall based on thermocouple readings has been developed. The model solves an inverse heat-conduction problem to determine the erosion and skull profiles using time averages of thermocouple signals from the lining. By monitoring the results from these wear profile calculations, indications may be obtained on the need to adapt the operation towards conditions less prone to cause erosion. In case of severe damage, the results can even be thought to trigger the planning of a relining of the hearth. The estimates from the skull calculations, in turn, can be used to assist in the interpretation of the internal state of the hearth. In this work, the calculated amount of skull has been verified by correlating this estimate with other key variables, such as production rate, hearth coke voidage, and pressure loss of the furnace. Some suggestions on how to control the amount of skull on the hearth wall, primarily by adjusting the cooling rate in this region, are finally presented.

2. Model for Calculation of Hearth Wear and Skulling

The calculation of the hearth wear and the amount of skull on the hearth wall is based on the commonly accepted procedure of estimating the location of the 1150°C isotherm in the hearth lining: Carbon saturated pig iron cannot exist below this temperature in liquid form, so this isotherm corresponds to the maximum hot metal penetration in the lining. The erosion profile is usually estimated as the most severe location of this isotherm experienced during the furnace campaign. If, in turn, the estimated location of the isotherm falls inside the erosion line, the volume between these two is considered to be filled with skull material.

The general ideas outlined above are followed in the present model, the kernel of which is a routine for calculating the temperature distribution in the hearth lining. To estimate the location of the 1150°C isotherm, the position of it that gives the best fit between the calculated temperature distribution and the temperatures measured by thermocouples located in the hearth lining is sought for. The temperature distribution is described by the cylindrical formulation of the heat equation⁸⁾

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(kr \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial \phi} \left(k \frac{\partial T}{\partial \phi} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + S. \quad (1)$$

No heat is generated in the hearth lining, so the heat source, S , can be neglected. As there will be only relatively small irregularities in the geometry, material properties and boundary conditions in the angular direction, the angular heat conduction was also neglected. This means that the task is reduced from a three-dimensional to a two-dimensional problem. Finally, steady state conditions are assumed

Fig. 2. Algorithm for determining the skull line in the blast furnace hearth.

to prevail, yielding

$$\frac{1}{r} \frac{\partial}{\partial r} \left(kr \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) = 0. \quad (2)$$

The assumption of steady-state conditions is motivated by the fact that the changes in the hot face as well as cold face boundary conditions are slow, so the temperature distribution in the hearth is almost static. This assumption is briefly discussed in the last section of this paper.

The calculation of the temperature distribution is based on a code for solving partial differential equations using the finite element method. To solve a heat conduction problem the geometry of the problem has to be defined together with the boundary conditions and the heat conduction coefficients of the hearth lining. Therefore, routines for the calculation of these prerequisites based on user input and thermocouple data were developed. In brief, the algorithm for the estimation of the location of the 1150°C isotherm is illustrated in Fig. 2. Normally, what is estimated is the thickness of the layer of skull between the erosion line and the 1150°C isotherm. If this thickness approaches zero then erosion is assumed to occur. The skull thickness is given by a vector, β , of the thicknesses at certain points along the skull line, and the skull line between these points is approximated with a suitable interpolation scheme. With more elements in β a more complex shape of the line can be described. However, there are only a limited number of thermocouple readings in the lining available, so the information about the temperature distribution is also limited. Thus, the complexity of the curve that can be robustly estimated is limited. With the hearth lining configuration of the blast furnaces studied in this work, a vector of $l=4$ unknown thicknesses was used along each line in the radial direction considered. With this parameterization, the model was robust while still flexible enough to express the shape of the skull line.

The cold face boundary conditions are calculated from thermocouple readings, while the other boundary conditions are given by the setup and solution of the problem. The hot face temperature is fixed at 1150°C, while the rotational axis and the upper wall boundary of the studied re-

Fig. 3. Finite element mesh, skull line, erosion line and location of the thermocouples (●).

gion (cf. Fig. 3) are zero heat flux boundaries. In the furnaces studied there are thermocouples at three different levels above the bottom plate in the hearth pad, as illustrated in Fig. 3. To limit the calculation domain and because the thermocouples on the bottom plate level give no additional information about the hot face conditions, only thermocouples on the upper two levels were used in the calculations. The lining between the bottom plate and the middle level of thermocouples will also act as a filter damping irregularities in the cooling before reaching the mid-level of thermocouples; this will aid the calculations. The temperature readings of the middle row of thermocouples give the boundary condition for the bottom of the computational domain. The cold face boundary conditions for the hearth wall are calculated from pairs of thermocouples in the lining (cf. Fig. 3). The boundary condition is then given by the heat flux

$$\dot{q} = k \frac{T_i - T_o}{r_o - r_i} \dots \dots \dots (3)$$

but it can equally well be given by the cold face temperature

$$T_c = T_o + \frac{r_c - r_o}{r_o - r_i} (T_o - T_i), \dots \dots \dots (4)$$

where subscripts o and i correspond to the outer and inner positions and c to the cold face, while k is the thermal conductivity of the lining material.

The skull line is determined for measurements on n different lines along the radius, i.e., at different angles, φ , to the taphole line, as indicated in Fig. 4(a). A quasi-newton optimization routine was used to find the skull thicknesses, β_φ (cf. Fig. 4(b)), that minimize the square sum of the differences between measured, T_m , and calculated, $\hat{T}$, temperatures at the locations indicated in Fig. 3. The elements, $\beta_{\varphi,j}$, of the thickness vector are expressed as

$$\beta_{\varphi,j} = \tilde{\beta}_{\varphi,j} B_j, \dots \dots \dots (5)$$

where B_j is the (preset) maximum skull thickness, while $\tilde{\beta}_{\varphi,j} \in (0,1)$ is the skull thickness in normalized form. To obtain such a normalization, the latter variables are calculated

b)

Fig. 4. Schematic illustration of a) lines along which skull and erosion lines are calculated, and b) of the parameterization of the skull thickness and of the residual carbon brick.

from the sigmoid

$$\tilde{\beta}_{\varphi,j} = 0.5 + \frac{\exp(\alpha_{\varphi,j}) - \exp(-\alpha_{\varphi,j})}{\exp(\alpha_{\varphi,j}) + \exp(-\alpha_{\varphi,j})}; \quad j=1, \dots, l \quad \dots (6)$$

and the elements of the auxiliary vector introduced, α_φ , are used as unknowns in solving the optimization prob

$$\min_{\alpha_\varphi} \left\{ E = \| \mathbf{T}_m - \hat{\mathbf{T}}(\beta_\varphi) \|_2^2 + \| \alpha_\varphi \|_2^4 \right\} \dots \dots \dots (7)$$

on the basis of measurements along a line forming the angle φ with the taphole line. In the objective function $\| \cdot \|_2$ denotes the Euclidean norm, and the last part of E is a regularization term, which was introduced to prevent the elements of α to take on extreme values. The objective function could also include a term that would penalize for large deviations between the values of “adjacent” elements of α in order to yield a smooth appearance of the skull line.

If the estimated skull thickness in a point is very small, this is taken to indicate that erosion occurs, and the closer to zero the thickness is the more rapid is the erosion. Thus, the erosion line, determined by the vector γ (cf. Fig. 4(b)), describing the residual amount of carbon, has to be adjusted accordingly in such situations. Calculations for different angles, φ , will usually yield different skull thickness esti-

mates at the rotational axis ($r=0$). Therefore, the l parameters for each sub-problem are first estimated independently. Next, the skull thickness in the center, β_1 , is calculated as the average of the skull thickness in the center for the different skull lines determined

$$\beta_1 = \frac{1}{n} \sum_{\varphi} \beta_{\varphi,1} \dots\dots\dots (8)$$

After fixing this value, the optimization routine is finally re-run for the remaining $l-1$ positions on the skull line for each angle, φ .

In solving the heat conduction problem, up to 100 calculations of the temperature distribution for each skull-line location may be needed to find the optimal line. Because the generation of the mesh consisting of about 500 triangles was found to be the most time-consuming step in solving the problem, a routine based on deforming an original grid to match the skull and erosion lines was developed. The introduction of this reduced the required computation burden considerably. Another factor that strongly influenced the computational effort was whether temperature-dependent heat conductivities of the lining materials were used or not. To make the solution procedure efficient, the temperature distribution of the previous solution (*e.g.*, for the previous day in the time sequences studied) was used to calculate the heat conductivity of the lining materials and the properties were then fixed and treated as constants. The heat conductivity of the skull material, in turn, was set once for all, but different values may be used for different locations along the hot face. If the properties of the skull at the hearth bottom are different from the properties of skull at the hearth walls, it may be desirable to use different heat conductivities in these areas. In the examples presented in this paper, however, this option has not been used.

3. Model Results and Validation

A case study of the performance and use of the skull and erosion calculations has been carried out on data from the two blast furnaces of Rautaruukki Steel in Raahe, Finland. Both are one taphole furnaces with a working volume of approximately 1 000 m³ and a production presently exceeding 3 400 metric tons/day. The iron-bearing material consists of sinter (70–80%) and pellets (30–20%), while about 330–350 kg of coke and 80–100 kg of oil are used as reducing agent. The hearth walls of the BFs are stove-cooled and air cooling of the bottom plates is possible. BF1 is equipped with a bell-top and BF2 with a bell-less charging equipment.

The data used consists of measurements since the last relines, BF1 being relined in 1995 and BF2 in 1996. The daily averages of 59 thermocouples located in the hearth lining, and tapwise data such as duration of tap and amount of tapped metal have been used in the study. Furthermore, five-minute averages of pressure measurements as well as of measurements of the burden descent rate have been used as supporting evidence to detect floating of the dead man.

3.1. Overall Behavior of the Estimated Hearth Profiles

Figure 5 shows estimated evolutions of the erosion lines and skull thicknesses for BF1 and BF2. Generally, it can be

concluded that the wear and skulling of the hearth of BF2 is considerably smoother and more well-controlled than in the case of BF1. These results conform with practical observations from the operation of the furnaces, which indicate that the behavior of the hearth of BF2 has been clearly superior to that of BF1. To illustrate this, Figs. 6(a) and 6(b) show 3-dimensional images of the hot face profiles 724 days (BF1) and 751 days (BF2) after blow-in. In the hearth of BF1 a low permeability leads to considerable amounts of skull on the walls, and cause problems with poor draining. During the later stages of the operation of BF1, there are sudden drops in the skull thickness at the wall (*cf.* Fig. 5(a)). Inspection of these using the 3-D interface showed that the changes start at the taphole region and gradually move towards the hearth center and finally to the wall on the opposite side. Figure 7 illustrates a typical time evolution of the skull thickness at the hearth bottom and at the taphole level opposite to the taphole. The two variables are clearly correlated, and there is a time lag of about one week between their responses.

3.2. Validation of the Model

In order to validate the model, efforts are made in this section to correlate the results with observations of other variables that depend on the state of the blast furnace hearth, such as tap variables, production rate and pressure drop.

3.2.1 Comparison with Estimated Hearth Coke Voidage and Slag Delay

The progress of erosion or growth of skull in the hearth is strongly connected to the flow conditions of slag and metal in this region. Since growth of skull on the wall will affect the fluid flow and therefore also the tapping of metal and slag, one would expect that changes in the amount of skull on the hearth wall could be observed in tap variables, *e.g.*, in the slag delay.

If the voidage of the hearth coke is low, the resistance to flow will be high, leading to low hot metal velocities. For a sitting dead man, where the hot metal cannot flow below the hearth coke, this will lead to build-up of skull on the hearth bottom, which should be observed with the model calculations. By using a model that provides a rough estimate of the hearth coke voidage on the basis of observed tap times and slag delays,⁶⁾ the relation between the hearth voidage and amount of skull illustrated in Fig. 8 was found. With decreasing hearth coke voidage, the amount of skull in the hearth increases, as expected. It should be pointed out that if the dead man is inactive, but still floats, the iron can adopt flow paths around or beneath it, and in such situations a similar correlation between the hearth coke voidage and the amount of skull would not be expected.

The slag delay, *i.e.*, the time it takes after the taphole has been opened for the iron/slag interface to descend to the taphole level, depends on many factors, the tap rate of iron during the initial stage of the tapping perhaps being the most obvious one. The higher the resistance to flow, the lower the tap rate, and thus the longer the slag delay. The amount of iron accumulated above the taphole prior to the tap is another important factor that affects the slag delay. However, the iron/slag interface will not remain horizontal during tapping, but will incline (towards the taphole) so that

Fig. 5. Estimation of the residual lining and the amount of skull for Rautaruukki BF1 (a) and BF2 (b). The upper sub-panels depict the mean skull thickness and residual lining for the wall, while the lower ones show the corresponding variables for the bottom.

iron is drained from the region below the taphole level.⁹⁾

Figure 9 schematically shows the blast furnace hearth with the dead man floating in the iron bath, as well as the inclinations in the iron/slag and slag/gas interfaces at the end of tapping. After the taphole is being closed, iron will start to accumulate, initially in the volume below the taphole from which it has been drained. Thus, a large inclination in the iron/slag interface, together with a high hearth coke voidage and a small amount of skull on the walls will increase this volume. This leads to a lower iron level before the taphole is opened, which, in turn, yields a short slag delay. High amounts of skull is connected to a long slag delay through low voidage, high resistance to flow, and a decrease of the effective volume below the taphole. It should, though, be noted that the relation between the flow

patterns of iron and slag and the inclination of the iron/slag interface is extremely complicated, and extensive CFD modeling would be required to fully clarify these effects.

In **Fig. 10**, the slag delay observed at BF2 of Rautaruukki for a period of 1.5 years (June 1997 to November 1998) has been compared with the estimated amount of skull at the hearth wall. (The latter variable was for the purpose of illustration scaled to facilitate comparison.) During the period changes in the skull thickness can be related to corresponding changes in the slag delay. An upward motion of the dead-man coke towards the raceways leads to the formation of a coke-free region in the hearth periphery, and the changed properties of this zone will strongly affect the liquid flow.¹⁰⁾ The period where the slag delay correlates with the skull thickness was found to coin-

cide with the period when the dead man (presumably) floats, as will be discussed later in the text. This seems to indicate that the slag delay depends on the existence and properties of a coke-free zone in the hearth corner. Changes in the flow rates in this zone will affect the build-up or ero-

Fig. 6. Hot face profiles for the hearth of the blast furnaces a) 724 days after blow-in of BF1 and b) 751 days after blow-in of BF2. The dimensions as well as the colors of the pictures indicate the extent of the wear. The black bar schematically denotes the angular location of the taphole.

sion of skull and can, therefore, be detected with the skull model.

3.2.2 Comparison with Pressure Drop and Driving Rate

Floating of the dead man in the hearth is the result of equilibrium of forces acting upon it.¹¹⁾ The buoyancy force of the hot metal bath varies with the volume of the hearth coke penetrating into the hot metal. With growing hearth volume, the lifting force acting upon the dead man will increase and the dead man will start to float. In the operation of the blast furnace, the short-term dynamics of the dead man are caused by the fluctuation of the levels of metal and slag in the hearth. For furnaces with one taphole, the dead man will be at its highest level at, or slightly after, the moment when the taphole is opened, and at its lowest level at the end of the tap. The movement of the dead man will usually exert influence on the gas flow in the lower part of the furnace, since the raceways and the cohesive zone may be affected. It should therefore be possible to detect pool level changes in measurements related to the gas flow. Generally, the pressure loss will follow the level of the (iron) bath in

Fig. 8. Relationship between the estimated hearth voidage⁶ and the amount of skull in the hearth estimated by the model.

Fig. 7. Typical time evolution of skull thickness in the taphole level (—) and at the hearth bottom (○—○) for BF1.

the hearth. **Figure 11** shows the measured pressure loss in BF2 over the normalized tap cycle for two different states ($t=260-300$ d and $t=760-800$ d, cf. Fig. 5(b)). In order to facilitate the use of data from several taps, the times of the tap cycle (taphole open/taphole closed) were normalized. In the upper panel, which corresponds to the operation in the beginning of the campaign, *i.e.*, to a furnace with a small hearth volume and a sitting dead man, no clear trend can be observed in the pressure loss. In the lower panel, which corresponds to operation under worn hearth lining, the pressure loss increases when iron and slag accumulate in the hearth, but decreases as the dead man sinks when the hearth is being drained.

The pressure loss in the furnace can also be related to tap data in the case of a floating dead man. In **Fig. 12**, the evolution of the pressure loss for low tapping rates of iron (amount tapped/tap time) is compared with the loss for high tapping rates. A low tapping rate results in less pronounced changes in the pressure loss, and, furthermore, delays the changes. The latter phenomenon is probably due to the fact that for low drainage rates the lifting force of the bath will not decrease until the taphole has been eroded, after which higher flow rates occur. Naturally, the change in the pres-

Fig. 9. Blast furnace hearth with the dead man (gray region) floating in the metal bath. The free space and the interface between metal and slag as well as between slag and gas at the end of tapping have been depicted.

sure loss during tapping could also be caused by the effect of the slag surface on the gas flow. However, for BF1 and for the early operation of BF2, where problems with drainage resulted in high slag levels, no clear relation between the pressure loss and the tap cycle could be detected. Furthermore, another indication of the movement of the dead man is given by observations of changes in the rate of burden descent, which correlate with the tap cycle during periods when the dead man (presumably) floats. **Figure 13** shows that the burden descent rate will increase as the dead man descends during the taphole open period.

The general problem with the method applied above to detect the movement of the dead man is that the pressure loss signal is affected by a number of other factors, so changes in it induced by the tap cycle can be hard to detect. To overcome this, the time was normalized according to the tap cycle (open/closed taphole). By considering data from a period of sufficient length (>1 month) the effect of changes in the pressure loss not caused by the tap cycle will cancel out, resulting in the curves illustrated in Figs. 11 and 12.

Fig. 11. Pressure loss during the tap cycle. The upper panel depicts the evolution when the dead man sits at the bottom and the lower panel the evolution for a hearth with a floating dead.

Fig. 10. Relationship between the slag delay and wall skull index for a period with a presumed floating dead man.

Fig. 12. Evolution of the pressure loss at low (upper panel) and at high (lower panel) mean tapping rates of iron. The tapping rates in the lower panel are approximately 50 % higher than the tapping rates in the upper panel.

Fig. 13. Evolution of the burden descent rate during the tap cycle.

The pressure loss observations do not give any information about the shape of the bottom of the dead man, but they only indicate that there is a movement of the dead man along with the tap cycle. The question thus arises as to whether the dead man floats completely or just in the periphery, where the pressure acting from above is smaller. The skull profile from the later stages of operation for BF2, also exemplified in Fig. 5(b), show that there is a ring shaped erosion zone in the hearth bottom but considerably less erosion in the hearth center. This suggests that the dead man would be in contact with the hearth bottom in the center, at least during part of the tap cycle, which would decrease the erosion in this region. The findings are in agreement with the elephant-foot shaped erosion that has been found in dissections of blown-out furnaces, but in the present case the erosion is not alarming. The change in the behavior of the pressure loss from being independent of the tap cycle to depend on the amounts of liquids in the hearth coincides with a high rate of erosion in the hearth corner (cf. Fig 5(b) at $t=370$ d). This indicates that high iron velocities in a ring-shaped coke-free zone were responsible for the erosion.

4. Possible Measures to Affect the Hearth Skull

In light of the findings presented above, this section

briefly discusses the effect on the state of the furnace hearth of some control actions “from below”. Other measures to control the state, *e.g.*, by changing the burden distribution, slag composition or coke properties, will not be discussed.

4.1. Hearth Bottom and Wall Cooling

Whether the skull on the hearth bottom and wall grows or is eroded depends on the amount of heat that the skull surface receives from the hot metal and the heat that is transported through the lining to the cooling system. Thus, the skull layer can be controlled either by changing the conditions inside the hearth or from the outside by changing the cooling rate. The cooling system is often designed for worst-case scenarios, corresponding to the conditions at the end of the campaign, with high flow rates of molten materials along the hot face and a thin remaining hearth lining. In such cases, it is necessary to remove a lot of heat to prevent the erosion line from proceeding further towards the cold face. In the earlier stages of the campaign, however, the hearth is usually not severely eroded. Instead, the problem may be the opposite, *i.e.*, a limited hearth capacity caused by skull growth or slow erosion. This may be the case if the furnace is operated at very high productivity before the furnace hearth has been eroded, resulting in problems with liquid drainage.

In the furnaces studied in this work some trials were made by switching the bottom-plate cooling on or off. The results were inconclusive; no clear relation between the skull thickness at the hearth bottom and the cooling rate of the bottom plate was found. An analysis by the model revealed that most of the heat transported from the hearth was conducted through the hearth wall, so the over-all effect of the said changes was quite small. The layer of highly conductive graphite above the bottom plate will transport a considerable amount of heat in the radial direction to the wall cooling system, thus reducing the influence of the bottom cooling. **Figure 14** illustrates the minor change in the temperature distribution and skull thickness for the cases with and without bottom cooling. Therefore, a more efficient approach would be to change the cooling rate of the hearth wall, but such a measure should be accompanied by a very strict monitoring of the hearth skull thickness and wear to prevent excessive erosion. However, it should be noted that in spite of the fact that the bottom cooling only slightly influences the total amount of removed heat, the long-term effects are hard to predict, since even small alterations in the hot face geometry may lead to changes in the hot metal flow pattern.

In some cases rapid wear of the hearth wall may occur, leading to high thermocouple temperatures in the wall. Often, an increase in the cooling water rate is seen as a countermeasure that would decrease such wear. However, the crucial factor to monitor, when estimating the effect of changes in the cooling rate, is the lining temperature at the cold interface, T_c , which can be calculated with Eq. (4). If this temperature is low, an increase in the cooling rate will not significantly lower this temperature, and thus will not affect the temperature gradient of the hearth lining

$$\dot{q} = k \frac{\partial T}{\partial x} \approx k \frac{T_h - T_c}{\Delta x}, \dots\dots\dots(9)$$

Fig. 14. Lining temperature distribution with (left panel) and without (right panel) bottom plate cooling. Thermal conductivities of the different parts: A: $k=2$ W/(m K), B: $k=3$ W/(m K), C: $k=15$ W/(m K) and D: $k=12$ W/(m K).

upon which the heat flow depends. From Eq. (9), where subscript h denotes the hot face, the relative change in the cooling rate, if the cold face temperature is changed by ΔT_c , can be calculated as

$$\frac{\Delta \dot{q}}{\dot{q}} = \frac{\Delta T}{T_h - T_c} \quad (10)$$

If the maximum allowed cold face temperature is 200°C, say, and the minimum achievable cold face temperature is 30°C, the maximum relative change in the cooling rate will be less than 20%. A rise in the hearth lining thermocouple temperatures without a simultaneous rise in the cold face temperatures suggests violent flow conditions in the hearth, and should thus be met by measures to control the hot metal flow velocities. A possible remedy would be a (momentary) decrease in the production rate or plugging of some tuyeres close to the worn region. If, on the other hand, the rise in the hearth lining thermocouple temperature is accompanied by a rise in the cold face temperature then an increase in the cooling rate could lower the cold face temperature. The effect of the change in the cold interface temperature on the cooling rate can be estimated using Eq. (10). Finally, it should be stressed that the hot face equilibrium is detectable through inspection of the temperature gradient in the lining and not by observing the absolute temperatures of the thermocouples.

4.2. Production Rate

An increase in production will lead to higher liquid velocities in the hearth, increasing the heat transfer efficiency between the liquid iron and the lining, which will cause the skull line to move towards the cold face. In Fig. 15, it can be seen that during periods with high production the amount of skull is small.

4.3. Tapping Practice

Because the erosion and build-up of skull on the wall are, in much, determined by the flow conditions in the hearth, the tapping practice clearly affects the hearth conditions. It is desirable to keep the taphole as long as possible to move the region with high flow rates away from the taphole. Short taps with high tapping rates will promote the existence of annular shaped bypass flows that reduce the slag delay, but also subject the hearth to elephant-foot shaped erosion as well as to erosion in the taphole region. The tapping practice is probably the fastest and most efficient way to control the hearth state from below because of its immediate effect on the flow conditions. Unfortunately, the length of the periods of plugged and open taphole are in practice deter-

Fig. 15. Hot metal production rate versus amount of hearth skull for BF2.

mined by factors, such as the quality of the taphole mud, the viscosity and chemical composition of the slag, and even on logistics of ladle or torpedo car transport in the works. There may thus be external constraints that overrule possible improvements in the internal state of the hearth achievable through changes in the tapping practice. However, a prerequisite for being able to use tapping practice as an efficient means to control the conditions is that the hearth state be known. The model described in this paper can be used to throw light on this complicated process system.

5. Discussion and Conclusions

A model for estimation of wear and skulling of the blast furnace hearth has been developed. The model has been illustrated on process data from two Finnish blast furnaces and it has detected clear differences in the general behavior of the hearth regions. BF1 exhibits a slower wear of the hearth lining, while BF2 shows a more uniform and regular, and well controlled, erosion. A reason for this may be the differences in the burden distribution, caused by differences in the charging equipment.

The results of the model have been verified using independent process measurements that reflect the state of the hearth. Trends exhibited by variables, such as slag delay, (estimated) hearth coke voidage, gas pressure drop and production rate have shown supporting evidence for the findings provided by the model. By combining its predictions with such observations, attempts have been made to inter-

Fig. 16. Simulated temperature response of the hearth lining at the position of thermocouples on the highest level in the bottom (lower panel) after a 24-hr pulse change in the hot face temperature (upper panel).

pret the internal state of the furnace hearth. Issues addressed are the state of the hearth coke, a possible floating of the dead man, and the general flow patterns of molten iron. Finally, a set of possible actions to control the conditions in the hearth has been discussed.

The model developed in this work is based on the assumption of steady state heat conduction in the hearth lining. Steady state can be considered a plausible first approximation, mainly because of the fact that long-term (here one-day) averages of the temperature measurements were used. For shorter “sampling” times, the simplification cannot be motivated. Rapid changes in the hot face boundary conditions may arise from sudden changes in the hot metal flow patterns, and this will result in considerably lagged temperature responses at the location of the thermocouples. Changes in the cooling rate may also set the lining into a dynamic thermal state. In order to show the importance to consider dynamics, **Fig. 16** illustrates the simulated effect of a 100°C pulse change in the hot face temperature that lasts for one day. It can be seen that there is substantial time lag before changes in the hot face boundary conditions reach the thermocouples in the furnace bottom. Also, notice the substantial decrease in the magnitude of the response at the thermocouples. The small changes in temperature of the thermocouples make the problem extremely sensitive to modeling and measurement errors: An error in the measured cold face temperature of about 3°C yields a change of 100°C in the hot face condition!

It is possible to use the time-dependent formulation of the heat equation (1) to calculate the location of the hot face boundary.¹²⁾ This approach has been tested on estimating the lining thickness in the hearth bottom.¹³⁾ However, since the method is sensitive to measurement errors, and even more so in a 2-dimensional formulation, the preliminary study was carried out in one dimension. Such a model could be primarily intended to evaluate the dynamics of rapid changes in the hot face conditions. The model presented in this paper, in turn, is suited for estimation of the skull thickness and long-term erosion and is to be used to-

gether with other process variables (e.g., tap data) to interpret the over-all performance of the hearth. Future work will be focused on a possible combination of the two techniques in a knowledge-based environment for hearth and tapping control.

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Nomenclature

- B : maximum skull thickness
- c_p : specific heat capacity (kJ/(kg K))
- E : euclidean norm
- k : thermal conductivity (W/(m K))
- l : number of parameters describing the skull line
- $\dot{q}$: heat flux (W/m²)
- r : radius (m)
- S : heat source (W)
- t : time (min, day)
- T : temperature (°C)
- $\hat{T}$: calculated temperature (°C)
- z : height coordinate (m)

Greek letters

- α : auxiliary vector used in optimization
- β : skull thickness
- γ : residual carbon thickness
- ϕ : angle (rad)
- η : density (kg/m³)

Subscripts

- c: cold face
- h: hot face
- i: inner
- j: location on skull line
- m: measured
- o: outer

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