An Experimental and Numerical Study of the Heat Flow in the Blast Furnace Hearth

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"Whether You Think You Can or Can't, You're Right"

Henry Ford
Abstract
This study has focused on determining the heat flows in a production blast furnace hearth. This part of the blast furnace is exposed to high temperatures. In order to increase the campaign length of the lining an improved knowledge of heat flows are necessary. Thus, it has been studied both experimentally and numerically by heat transfer modeling. Measurements of outer surface temperatures in the lower part of a production blast furnace were carried out. In the experimental study, relations were established between lining temperatures and outer surface temperatures. These relations were used as boundary conditions in a mathematical model, in which the temperature profiles in the hearth lining are calculated. The predictions show that the corner between the wall and the bottom is the most sensitive part of the hearth. Furthermore, the predictions show that no studied part of the lining had an inner temperature higher than the critical temperature 1150°C, where the iron melt can be in contact with the lining.
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Maria Swartling

Maria Swartling, Stockholm, December 2008
Supplements

The present thesis is based on the following papers:

**Supplement 1:** “Experimentally determined heat flows in a blast furnace hearth”  
*M.Swartling, B. Sundelin, A. Tilliander and P. Jönsson*

**Supplement 2:** “Heat transfer modeling of a blast furnace hearth”  
*M.Swartling, B. Sundelin, A. Tilliander and P. Jönsson*

Parts of this work have been presented at the following conference:

“Temperature measurements on Blast Furnace 2 at SSAB Oxelösund”  
*M.Swartling, B. Sundelin, A. Tilliander and P. Jönsson*  
3rd Nordic Conference for Young Scientists, 14-15 May 2008, Helsinki, Finland.

The contributions by the author to the different supplements of the thesis:

1. Literature survey, experimental work, major part of the writing.  
2. Literature survey, numerical calculations, major part of the writing.
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1 Introduction

The blast furnace is a very important reactor in the route of steelmaking. As much as 67% of all steel produced in 2007 was ore based and the blast furnace processes stands for 95% of the world’s ore based production.\textsuperscript{1} Even though the blast furnace process is old, it is under constant development. Today, the main focus is on extending the campaign length, increasing the productivity, decreasing the coke rate and decreasing the CO\textsubscript{2} emissions.

The blast furnace hearth is exposed to high temperatures as well as liquid metal and slag, causing both erosion and corrosion of the refractory material. An increased productivity results in higher load on the furnace hearth and thereby causes difficulties with increasing the campaign length. Keeping this part of the lining at a low and steady temperature is crucial. Thus, as a part in reaching the goals, an improved process control is required. A better control of the heat flows in the hearth would also lead to energy savings, since the cooling requirements can be better understood and the use of excess water avoid.

The present thesis has focused on determining the heat flows in a production blast furnace hearth, both experimentally and by heat transfer modeling.

There are two ways of approaching a heat transfer problem: direct and inverse heat conduction, known as DHCP and IHCP respectively.\textsuperscript{2} The DHCP formulation is used when boundary conditions and thermophysical properties of the system are known. For the IHCP approach, either the thermophysical properties or the boundary conditions can be unknown; instead, the temperature of the interior has to be known for some points of the domain.
Previous heat transfer models performed by other authors are reviewed in the following literature survey. During the development of a model, the two main steps are the formulation of boundary conditions and the validation of calculation results; this review has focused on these two steps.

For a DHCP formulation, the inner surface temperatures are in some models set equal to the temperature of the melt\(^3\)-\(^6\), meaning that the melt is assumed to be in direct contact with the wall. However, this is not always the case in an industrial blast furnace. An IHCP model is based on the solution of the boundary surface conditions, e.g. the temperature of the hot surface, by utilizing measurements from inside the lining.\(^7\)-\(^8\)

The outer surfaces can be defined by setting a cooling medium, such as water, oil or air, at constant temperature together with a heat transfer coefficient\(^3\)-\(^6\) or to define constant a temperature on all outer surfaces\(^9\).

The most common model validation method is to compare calculated temperatures with data from thermocouples. The extent to which previous models have been validated varies from comparisons with a large number of thermocouples measurements, to no comparison at all. What is considered to be good agreement between calculated and measured temperatures varies from minus 40 to plus 50°C in the studied papers.\(^3\)-\(^11\)

A summary of the literature survey can be seen in Table 1. The table shows whether the studied models are separate heat transfer models or combined heat and fluid flow models. It also shows if the model is a DHCP or an IHCP model. If the paper presents a comparison between calculated temperatures and measured lining temperatures, then the accuracy of the model is shown in Table 1. The authors have read the values from text, graph or table in the respective paper. In general, the largest differences are presented in degrees Celsius, but in one case the average difference is given.
Table 1 Summary of literature survey. The values in Accuracy of model are read by the authors from text, graph or table.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Separate heat model</th>
<th>Combined heat and fluid model</th>
<th>DHCP</th>
<th>IHCP</th>
<th>Accuracy of model in degrees Celsius</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>Average diff. 12.7%</td>
</tr>
<tr>
<td>4</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>+37/-40</td>
</tr>
<tr>
<td>6</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>+43/-10</td>
</tr>
<tr>
<td>9</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>+50/-10</td>
</tr>
<tr>
<td>10</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>+40/-20</td>
</tr>
<tr>
<td>Current study</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>±3</td>
</tr>
</tbody>
</table>

The overall purpose in this thesis is to develop a reliable model of the heat flow in the blast furnace hearth. This model should utilize temperature data, which are available in a production furnace. At the same time the model should represent an improvement to the models presented in the open literature. Thus, one aim has been to reduce the number of assumptions needed for the heat transfer model. This has been done by first carrying out manual temperature measurements on the outer surfaces of the furnace wall and bottom thereafter by comparing these data to lining temperatures. The experimental study is presented in detail in Supplement 1. The specific aim of the experimental study was to establish a relation between surface and lining temperatures. To the authors’ knowledge, measurements of surface temperatures have not been presented in the open literature. In the second part of the work, the results from the measurements are used in the heat transfer model development. The methodology of the model is presented in detail in Supplement 2.
2 Plant description

2.1 SSAB Oxelösund
SSAB Oxelösund is an integrated ironworks, steelworks and rolling mill; the production chain starts with raw iron material and ends with a finished plate. The ironworks has two blast furnaces, Blast Furnace No. 2 and Blast Furnace No. 4, producing 2000 and 3000 metric tonnes of pig iron a day respectively. Both are charged with pellets as the iron-bearing material and coke from the company’s own coke plant. The pig iron is transported with torpedoes to the steelworks, at which the pig iron is converted into steel and the composition of the steel is set. The steel is then cast into slabs. The slabs are rolled into heavy plate, heat treated and hardened in the rolling mill. The annual slab production is 1.6 million metric tonnes, of which some is exported. Furthermore the production of heavy plate is 586 000 metric tonnes (2006). The company’s special fields are quenched and tempered steels with brand names such as HARDOX and WELDOX. 12

2.2 Details of Blast Furnace No. 2
The current study is performed on Blast Furnace No. 2. Figure 1 shows a cross section of the hearth schematically outlined. The lining consists of different refractory zones: wall, bottom, ramming material, a ceramic plate and a steel shell. The lining is equipped with permanently installed thermocouples; these are placed in five levels, numbered from 0 to 4 as pointed out in the figure.
The outer wall is water cooled to a position just above the bottom; the water flows down to a vessel placed above level 1 (Figure 1). Subsequently, levels 2-4 are constantly cooled with water, while levels 0-1 are exposed to the surrounding air. The bottom is equipped with pipes for water cooling; the pipes are placed 30 cm apart. Each pipe is connected to the adjacent pipes and the water circulates through all pipes. The cooling is turned on when it is decided to be needed.

![Figure 1 Schematic picture of the hearth, and its position in the blast furnace. A two-dimensional cross section represents a specific angle from the tap hole.](image)

### 2.3 Characterization of the state of the hearth of Blast Furnace No. 2

In an earlier study, the state of the hearth was characterized as the blast furnace was taken out of operation to be relined. Figure 2 is a photograph taken during the deconstruction of the furnace. Material zones and skull are marked in the figure.
Visual observations showed that the lining wear was minor. The ceramic plate was almost intact, but the pores were penetrated by drops of iron. However, overall it was no erosion of the bottom lining. Some erosion of the wall had occurred. It is seen in the figure that the wall lining blocks does not have its original rectangular shape. Nevertheless, the erosion was considered to be minor. Thus, considering the state of the hearth, the campaign length could have been extended. During the end of the campaign, thermocouples had registered high temperatures, indicating erosion of the lining. The phenomenon causing the high temperatures were probably plates of iron that had solidified in cracks and seams.¹³
3 Experimental study

In the experimental study the temperature was measured at the outer surfaces of the hearth wall and bottom using a hand-held thermocouple. When measuring the wall surface temperature, the thermocouple was put in direct contact with the surface. Measurements were performed at heights corresponding to level 1-4 (see Figure 1). For water cooled levels 2-4, the water was not turned off or in any other way removed. When measuring bottom surface temperature, a thermocouple with a long wire was attached to a bar. The bar was inserted through a cooling pipe a certain distance. The rod was pulled out of the cooling pipe a short distance at the time, measuring temperature at each distance. The bottom measurements were performed when no water cooling was needed. Figure 3 shows the bottom measurements in progress.

Temperature was read when the display showed a stable value which fluctuated less than 2-3°C. The thermocouple used was a CIE 305 Thermometer with a probe of type K (NiCr-NiAl). The accuracy of the instrument was ±0.3% + 1°C in the measuring interval. The accuracy of the probe was ±0.75% of the temperature in °C or ±2.2°C (whichever is greater)\textsuperscript{14}. 
Figure 3 Bottom temperature measurements in cooling pipe in progress.
4 Mathematical model

A mathematical model of the hearth of the blast furnace has been developed. In this chapter, a summary of the model is presented.

4.1 Numerical assumptions
In order to simplify the calculations the following assumptions were made:

- Two-dimensional
- Steady state
- No heat generation within the system
- Only solid materials, i.e. no mass transfer

It should be noted that even though the model is set up as two-dimensional model, each cross-section is unique and axial symmetry is not assumed.

4.2 Energy equation
The equation of energy to be solved has the following form in Cartesian coordinates and constant density and heat conductivity\(^2\):

\[
\rho C_p \left( \frac{\partial T}{\partial t} + v_r \frac{\partial T}{\partial r} + v_h \frac{\partial T}{\partial h} + v_z \frac{\partial T}{\partial z} \right) = k \left( \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial h^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{S_0}{k}
\]

(1)
where

\( \rho = \) density

\( C_p = \) specific heat capacity

\( T = \) temperature

\( t = \) time

\( v_i = \) velocity in i-direction

\( k = \) heat conductivity

\( S_0 = \) heat source

\( r, h, z = \) coordinates

When considering the given numerical assumptions, the following terms of equation 2 will be removed:

\[
\rho C_p \left( \frac{\partial T}{\partial t} + v_i \frac{\partial T}{\partial r} + \frac{\partial T}{\partial h} + \frac{\partial T}{\partial z} \right) = k \left( \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial h^2} + \frac{\partial^2 T}{\partial z^2} \right) + S_0
\]  \hspace{1cm} (2)

The final equation to be solved has the form:

\[
\frac{k}{\rho C_p} \left( \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial h^2} \right) = 0
\]  \hspace{1cm} (3)

### 4.3 Boundary conditions

Figure 4 shows a cross section of the computational domain. The dots in the interior represent thermocouple positions, numbered 1-14. Boundary positions are marked with dots denoted a-p. Three axes are defined: height, h; distance from wall, d; bottom radius, r. The boundaries are divided into three categories: adiabatic, outer and inner boundaries. The outer boundaries are calculated based on measurements from lining thermocouples. The relations between lining and outer surface temperatures are based on the findings in the experimental study in Supplement 1, some of which are presented in the Results and Discussion section.
4.4 Material properties

The thermophysical and thermodynamic properties required as input in the mathematical model are density, heat conductivity and specific heat capacity. The properties are listed in Table 2.\textsuperscript{15-17}

Table 2 Lining material properties. T is the temperature in Kelvin.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Material</th>
<th>Density $\rho$ kg/m$^3$</th>
<th>Heat Conductivity $k$ W/m K</th>
<th>Specific heat capacity $C_p$ J/kg K</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Wall</td>
<td>Carbon 1610</td>
<td>17</td>
<td>1.459T+367.5</td>
</tr>
<tr>
<td>B</td>
<td>Shell</td>
<td>Steel 8030</td>
<td>30</td>
<td>449</td>
</tr>
<tr>
<td>C</td>
<td>Ceramic plate</td>
<td>Mullite 2500</td>
<td>2</td>
<td>1200</td>
</tr>
<tr>
<td>D</td>
<td>Bottom</td>
<td>Carbon 1570</td>
<td>10</td>
<td>1.739T+486.1</td>
</tr>
<tr>
<td>E</td>
<td>Ramming material</td>
<td>Carbon 1610</td>
<td>60</td>
<td>1.739T+486.1</td>
</tr>
</tbody>
</table>
4.5 Calculation procedure

Data from thermocouple readings are inserted to the model and the initial boundary conditions are determined. The energy equation is solved in Fluent version 6.2.26. As a result from the calculation, the temperatures from the coordinates corresponding to the thermocouple positions are returned. The calculated values are compared to the measured lining temperatures. If necessary, the boundary conditions are adjusted and a new calculation is performed. As a final calculation result, a complete two-dimensional temperature profile of the lining is returned.

The condition to terminate the procedure is when the calculated and measured lining temperatures agree within ±3 degrees for all thermocouple positions. This is a condition assumed to yield sufficient accuracy of the calculations, based on the technical tolerances of the thermocouples installed. The methodology of the calculation procedure is shown in Figure 5.

![Figure 5 Calculation procedure.](image-url)
5 Results and discussion

In the first part of this chapter, some of the results from the experimental study are highlighted. Then calculation results from the mathematical model will be presented and discussed.

5.1 Experimental study

5.1.1 Lining temperature

Lining temperature data from thermocouples on level 1 and level 2 are presented in Figure 6. The thermocouples are placed at the same angle from the tap hole and at the same radius. The temperature data reaches from November 2006 to May 2008. Included in the figure is Average-Difference which is the temperature difference of level 1 and level 2 minus the average temperature difference of the last 14 days.
When studying the temperature data, it can be seen that there are periods of local maximum or minimum. Under steady conditions the value varies around zero (i.e. when the temperature difference is equal to the average value of the last 14 days). When a heat front enters the lining, it is registered in one of the levels before the other, and is therefore seen as a local peak in the Average-Difference-curve. The clear peaks are marked in the figure with vertical lines. The peaks often occur some days before the local maximum or minimum temperature. The line is based on historical temperature data, but with the advantage that it is visually easier to detect when the value, with a clear peak, deviates from zero. The manual surface temperature measurements were performed during steady blast furnace operation, when the value of the Average-Difference-curve is close to zero.

5.1.2 Wall surface temperature
Wall temperature measurements from one measuring occasion (January 16, 2008) are presented in Figure 7. The height along the outside of the shell is on the vertical axis and the horizontal axis shows the temperature. The different lines represent the angle from the tap hole, see Figure 1. The four measuring positions at each line represent levels 1-4.
The wall temperature seems to be constant at the water-cooled part of the furnace wall (levels 2-4 at height -0.6 to 1.6 m) and higher at the non-cooled part of the wall (level 1 at height -1.2 m).

Figure 8 shows the temperature profile at level 3 for two different angles from the tap hole, for one measuring occasion (January 8, 2008). The temperature is given on the vertical axis and the horizontal axis shows the distance from the outside of the shell. Distance 0 mm is the surface temperature, and at distance 170 and 370 mm are the lining temperatures.
The temperature profiles are linear; linear adaptations give a $R^2$-value close to 1. This means that it is possible to calculate the surface temperature by making a linear adaptation between the lining temperatures and then extrapolate the curve to the surface. These results also indicate that the hearth was in a thermal steady-state during the measurements.

### 5.1.3 Bottom surface temperature

The bottom surface temperature measurements are presented as the temperature along the radius at different angles from the tap hole. Examples of the results from measurements performed February 14, 2008, are seen in Figure 9. The temperature is plotted along the radius for the angles $0^\circ$ and $150^\circ$ from the tap hole. The filled circles represent experimentally measured surface temperatures; the unfilled circles are lining temperature measured by thermocouples on level 1 along the same radius.

![Figure 9 Bottom temperature profiles.](image)

From the temperature measurements it is seen that the bottom temperature profiles do not have a constant slope. There is one slope at the center part of the bottom and another steeper slope from radius 1-1.25 m. The same two slopes are found for those angles where at least two thermocouples are placed at a radius larger than 1 m.
5.2 Mathematical model

5.2.1 Temperature profile calculations
Figure 10 shows the lining temperatures at three thermocouple positions during a period of 90 days. Two of the positions are in the bottom (level 1 and level 2) and one position is in the wall (level 3). By using the developed model, temperature profiles were calculated for a few occasions chosen during this period (day 32, 40, 48, 56, and 70). In these calculations the transition from a steady period to an unsteady period, and back to a steady period can be studied. It should be noted that this studied period has the highest lining temperature registered during the whole 2.5 years campaign length of the blast furnace, and thus represents an extreme situation.

![Lining temperature 240 degrees from tap hole](image)

**Figure 10** Lining temperature during a 90 days period, starting at October 20, 2007.

In Figure 11 the calculated bottom temperatures at radius 0 m are presented for two positions: the inner surface and the seam between the ceramic plate and the bottom (carbon refractory). The material zones are indicated in Figure 1. The temperature 1150°C is included in the figure, which is the solidification temperature for carbon saturated iron. The bottom center furnace part is where the highest lining temperatures are found.
5.2.2 Evaluation of boundary conditions
The experimental study that established the relations used as boundary conditions was performed during steady blast furnace operation. The outer boundary conditions for three dates representing a steady blast furnace operation and one date representing an unsteady operation are presented in Figure 12; the unsteady date chosen is day 48 in the studied time period. The horizontal axis shows the initial boundary conditions, based on the relations found in the experimental study. The vertical axis shows the final adjusted boundary conditions.

Figure 11 Bottom temperature at radius r=0 m.
For the dates representing the steady periods, the boundary conditions are adjusted up to maximum 5 degrees. However, more adjustments are needed for the unsteady period. The adjustments are mainly needed at the upper part of the wall. This indicates that the water cooling is not enough to keep the wall at a constant temperature under unsteady conditions.

5.2.3 Skull layer

When creating the model geometry the whole lining was initially assumed to be intact. That assumption is based on the observations from the characterization study; the studied furnace is constructed by mainly the same materials as before the relining.\(^1\) If the temperature of the inner surface exceeds 1150°C, the iron melt can be in contact with the lining, causing erosion and corrosion of the refractory materials. If, however, the temperature of the inner surface is less than 1150°C, a solidified layer of melt mixed with coke, called skull, is assumed to protect the lining. Calculations of temperature profiles showed that the studied part of the lining was colder than the critical temperature 1150°C, even for the highest temperature registered during the campaign.

It is therefore of interest to calculate the skull thickness. Details of the calculations are given in Supplement 2. The results of the calculations for one position of the
bottom and one position of the wall are seen in Figure 13 and Figure 14. The calculations are based on one-dimensional heat transfer calculations with a heat conductivity value of 2 W/mK for the skull material. In the figure, each bar represents a cross-section of the lining from the outer shell to the skull layer.

**Figure 13** Bottom layer thickness at radius \( r = 0 \) m.

**Figure 14** Wall layer thickness at height \( h = 3.2 \) m.
The skull thickness during the studied period was in the range of 0.21-0.74 m and 0.17-0.90 m for the bottom and the wall thickness respectively. This is approximately in the same range as in a study by Torrkulla et al.\textsuperscript{10}, where the bottom skull thickness was in the range of 0.2-0.95 m and the wall thickness in the range of 0.25-0.85 m, within a period of 200 days.

During the characterization study it was concluded that the wall skull material consisted of blast furnace slag mixed with coke.\textsuperscript{13} When slag covers the hearth wall, the mechanism causing it may not only be solidification; a cold wall can cause a local increase of the slag viscosity, and as a consequence it adheres to the wall. Taking that mechanism into consideration, skull thickness calculations become far more complicated.

\textbf{5.2.4 Inner surface temperature}

In Figure 15 the bottom temperature along the h-axis (for axes, see Figure 4) is presented for a constant radius of 1.25 m. The different lining materials are marked in the figure, and the positions of these in the blast furnace are given in Figure 1. The temperature curves are linear, but with different slope for each material zone. When studying the slopes for each material zone, it was found that the quotient between the slopes of the different material zones were almost equal for every studied date. This is important for future process control, since it enables quick estimations of the inner surface temperature directly from thermocouple readings in the carbon refractory zone.
5.2.5 Thermocouple location

When the state of the hearth was characterized, the inner corner was exposed to the most wear during the most recent campaign. In this area, no thermocouples are located, and a suggestion is to install thermocouples in this exposed corner. The positions are marked with stars in Figure 16. The highest temperature occurs at the inner bottom. It could therefore be of interest to measure the temperature as close to the inner surface as possible. The highest place to install thermocouples would be in the seam between the ceramic plate and the carbon refractory; these positions are marked with triangles in Figure 16. Existing thermocouple positions are marked with circles.
Figure 16 Existing thermocouple configuration (circles) and suggestions of new thermocouple positions (triangles and stars).

The suggested thermocouples would improve the validation of the heat transfer model; moreover, skull layer calculations would be possible for the exposed corner area. Installing the corner thermocouples would be possible during the current campaign. However, the suggested bottom thermocouples can only be installed during a relining.
6 Conclusions

It is important to carefully control the temperature of the hearth lining during a blast furnace operation in order to have a long operational life-length of the furnace. This study has focused on determining the heat flows in a production blast furnace hearth, both experimentally and numerically. First, measurements of temperatures in the lower part of a production blast furnace were carried out. Second, a heat transfer model was developed, which was used to calculate the temperature profiles in the hearth lining.

The specific conclusions from the study may be summarized as follows:

- For those positions in the furnace bottom, defined as angles, where thermocouples are installed, the outer bottom and wall temperatures can be calculated.
- The relations established in the experimental study can be used as boundary conditions in the mathematical model with sufficient accuracy for steady blast furnace operation. During an unsteady operation, some adjustments are needed.
- It is possible to quickly estimate the inner surface temperature directly from thermocouple readings, by using a calculated quotient between the heat flow through the ceramic plate and the heat flow through the carbon refractory.
- The corner between the wall and the bottom is identified to be the most sensitive part of the lining. It is suggested that thermocouples are installed in this area, to improve the temperature control and enable skull layer calculations.
• For a studied time period, with a large lining temperature increase, no part of the lining at the studied angle had an inner temperature higher than the critical temperature 1150°C. During the time period the bottom skull layer thickness varied between 0.21-0.74 m, based on one-dimensional heat transfer calculations using a heat conductivity value of 2 W/mK for the skull material.

Overall, the results of this study show that the current modeling approach is very useful to determine suitable locations of thermocouples. Furthermore, it has the potential to be used to suggest how the cooling conditions at the bottom and the wall can be optimized in order to decrease variation in temperatures in the lining. This, in turn will increase the operational lifetime of a blast furnace. It can also lead to energy savings, since the cooling requirements can be better understood and the use of excess water avoid.
7 Future work

- Improve boundary conditions and model validation with the new suggested thermocouple positions.
- Skull layer calculations for more positions of the inner surface, specially the corner area, including chemical analysis of skull material.
- Extend the heat transfer model to include the unsteady tap hole area.
- Model the tap cycle, including both the heat flow and the fluid flow.
- Study the effects of different cooling conditions on the temperature distribution in the hearth.
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