A Study on the Thermal State of Steelmaking Ladles

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Doctoral Thesis

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ABSTRACT

In the present thesis a study on the thermal state of steelmaking ladles was undertaken. The transient hot wire method was verified for thermal conductivity measurements on metallurgical slags and applied to ladle slag measurements. Temperature measurements on ladles in an industrial environment were carried out. The emissivities of the outer and inner shells of steelmaking ladles were investigated. Two dynamic models were developed to predict the heat transfer and fluid flow in a preheating and teeming ladle. The gathered thermal conductivity values for ladle slag were used to study the effect of the slag layer on the top surface of the melt on heat transfer and fluid flow in a teeming ladle.

In the first stage, the transient hot-wire method was verified to measure the thermal conductivity of metallurgical slags at steelmaking temperatures. A numerical model was developed, cold model experiments were conducted and test measurements using a high temperature experimental setup were carried out. To minimize natural convection and to obtain more reliable measurements, the crucible diameter, the hot-wire diameter, the applied current, the position of the wire in the crucible and the cooling on the upper surface of the crucible were studied. Investigations into the choice of sheathing material of the circuit exposed to the slag were also made. It was found that only certain materials were suitable for slag measurements depending on slag composition and temperature. The electrical resistivity of the hot wire was measured to make the thermal conductivity calculation more reliable. The wire diameter also played a major role due to the heat generation per surface area. The thermal conductivity should be derived from the values measured during the first seconds. In this initial stage, the effect of the natural convection as a function of the wire position in the crucible, the cooling on the top surface and the diameter of the crucible are negligible. A compromise has to be made in choosing the electrical current, since higher current results in higher sensitivity but at the same time in more natural convection.

In the second stage, the thermal conductivities of four different ladle slags were measured at 1773 K, 1823 K, 1873 K and 1923 K using the transient hot wire method. Very good reproducibility was obtained. The thermal conductivity did not vary substantially with the variation of slag composition at 1873 K and 1923 K, at which the slag samples were all entirely liquid. The thermal conductivities were low. It was found that the precipitation of solid phase resulted in a considerable increase of thermal conductivity.

In the third stage, a two dimensional model was developed in order to predict the temperature distribution in the ladle wall during the preheating process. The model calculated the heat transfer and the velocity field in the gas phase inside the ladle as well as the heat transfer in the solid walls during the preheating process. Measurements of the temperature profiles in an industrial ladle were carried out using an infrared thermography. The measurements were made both inside and outside the ladle. The model predictions were found to be in reasonably good agreement with the measured temperatures. It was found that the preheating time could be minimized when the working lining became thinner. The effect of the distance between the
lid and the ladle was also studied by the model. The results indicated that there was no significant temperature change on the upper side wall of the ladle. On the lower side wall and bottom the temperature changed slightly. The temperature difference in the lower part of the ladle could be explained by the larger flame distance from the bottom layer.

In the fourth stage, a two dimensional axisymmetric model was developed to predict the heat flux in a steelmaking ladle during the teeming process. The model predicts dynamically the flow fields in both the liquid phase and the gas phase along with the movement of the liquid upper surface. The model also predicts the temperature distributions in the liquid metal, gas phase and all layers in the ladle wall. Again, industrial measurements were performed using an infrared thermography, both inside the ladle after teeming and at the wall outside the ladle during the whole process sequence. The model predictions were found to be in agreement with the measured data. It was found that the heat transfer to the surrounding atmosphere and the conductivity of the highly insulating layer were the most important factors for the heat loss. The decrease of the thickness of the working lining was found to have limited effect on the total heat flux.

In the fifth and final stage, the effect of the slag layer on the top surface of the melt, on fluid flow and on heat transfer in a teeming ladle was investigated theoretically. The two dimensional axisymmetric model developed in the fourth stage was used. To predict the effect of the slag layer a stationary heat conduction boundary condition including thermal conductivity and slag layer thickness was employed. Different calculations with differing thermal conductivity values for the slag layer were carried out. The calculations showed that the effect of the slag layer was insignificant. This could be explained by the similarity of the thermal conductivity of slag and gas phase.
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Stockholm, September 2012

Björn Glaser
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“Determination of experimental conditions for applying hot wire method to thermal conductivity of slag”

*Björn Glaser*, Luyao Ma and Du Sichen

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**Supplement 2:**
“Thermal conductivity measurements of ladle slag using transient hot wire method”

*Björn Glaser* and Du Sichen

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**Supplement 3:**
“Thermal modelling of the ladle preheating process”

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“Fluid flow and heat transfer in the ladle during teeming”

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**Supplement 5:**
“The effect of the slag layer on fluid flow and heat transfer in a teeming ladle”

*Björn Glaser*

Considered for later publication
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5. SUMMARY

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1. INTRODUCTION

The increasing demand for more specialized high quality steel grades as well as energy savings drive the ongoing optimization of steelmaking processes. Steelmaking operations in general, and casting operations in specific, require good temperature control. In the steel making process the quality of the steel is strongly influenced by the temperature of the liquid metal entering the continuous caster. Accidentally increasing or decreasing the steel temperature can result in poor steel quality, faster erosion of the refractory material and increased energy consumption. The heat losses from the steel are dependent on the ladle thermal status as well as the thermal properties of liquid steel and slag. The thermal status is determined by the refractory thermal history from previous heat cycles and the ladle refractory configuration and wear. To have a better control of the production process, the final steel composition and to achieve the desired casting temperature, the thermal status and the thermal properties of liquid steel and slag should be quantified. Especially the thermal conductivity of slag plays a critical role in the different steps of the steelmaking process. Consequently, a thorough understanding of the ladle thermal status and related heat fluxes are needed in all processing steps.

1.1 Background

Ladles are used to transport molten steel in a steel plant. A ladle cycle starts as the furnace starts tapping liquid steel into the ladle. The full ladle is transferred between stations for further processing of the steel. Typically, the ladle treatment starts with a combined deoxidation/desulphurisation treatment at a stirring station. A slag rake removes the top slag before the next step. Further processing is then performed at a ladle furnace. After slag building, a final composition adjustment and temperature trimming is performed. The ladle treatment at the secondary steelmaking operations is finished when the desired steel temperature and composition have been obtained. The ladle is then transferred to the caster operations where the teeming process is performed. After the casting process, the lid of the ladle is removed, the slag is poured out and the ladles are passed off for maintenance. In case the ladle is not used within a predefined period of time for the next casting cycle, the ladle needs to be preheated to avoid too low temperature of the ladle wall in the next heat. Low temperature of the ladle wall could lead to thermal shock when the ladle is filled with hot liquid steel and could potentially destroy the lining. Sufficient preheating is also necessary to avoid excessive heat losses of the liquid steel when it is poured into the ladle. Great effort is currently made to control the ladle thermal state throughout the entire steelmaking process chain.\[^{1-15}\] Some of these works focus on the development of a dynamic model for the preheating process.\[^{3-8}\]

The amount of heat stored in the ladle refractories is considerable and the heat fluxes during a ladle cycle influences the steel processing (temperature control) and the refractory lifetime (thermal stresses). Due to the nature of the refractory materials, changes in the wall/bottom temperature profile is a slow process and events taking place on the previous heat cycle could
have a strong influence on the next heat cycle temperature losses. Consequently, a thorough understanding of the ladle thermal status and related heat fluxes are needed in all processing steps to obtain a full view. A better understanding of the steel temperature losses during the teeming process will cause less "overheating" to take place in the secondary operations of steelmaking. It is today standard practice to aim for a slightly higher temperature than needed to stay safe and avoid caster sequence breaks if unexpected heat losses occur. Only a few degrees lower steel temperature on arrival to casting represents a considerable amount of energy. Therefore, the temperature distribution in a teeming ladle is of current interest to many steel producers and a relevant topic of researchers.[9-13]

While ladle slag plays very important roles in steel refining, the slag layer also protects the liquid steel from re-oxidation and acts as an insulator to reduce the heat loss from the melt to the surroundings during teeming. Because of the lack of thermal conductivity data, the function of the slag layer is very often excluded in dynamic models. The effect of the slag layer on the temperature distribution of the melt in a ladle during holding period and teeming process has been already investigated by several researchers.[2,9-11,14-15]

Measuring the thermal conductivity of slags at temperatures beyond 1773 K is exceedingly difficult for many reasons, as evidenced by the lack of data above this temperature for many common slag compositions. For high temperature thermal conductivity measurement of slag it has been found that the transient hot wire method has the highest accuracy and is mainly used above 1773 K. There are only a few available works that measured the thermal conductivity of slag at high temperatures.[16-22]

1.2 Present Work

In steelmaking, the slag layer on the top of the melt plays a critical role in the different steps of many processes. During the teeming process a slag layer is always kept to protect the steel melt from re-oxidation and to reduce the heat loss from the melt to the surroundings. Heat is transferred by conduction, convection and radiation. To be able to properly control the heat transfer in the teeming ladle, accurate thermophysical property data are necessary, where thermal conductivity is one of the most important properties.

The main focus of Supplement 1 was to determine the conditions for using the transient hot-wire method to measure the thermal conductivity of metallurgical slag systems. To reach this goal, CFD calculations were made and cold model experiments were conducted to determine the optimized experimental conditions. Finally, test measurements of a ladle slag at high temperature were made to examine the reproducibility of the technique and the suitability of the refractory materials.

Because of the lack of thermal conductivity data, the function of ladle slag is very often excluded in dynamic thermal models. To the knowledge of the present authors, no thermal conductivity data have been reported for ladle slags. Ladle slag is usually chosen in the high CaO containing region in the quaternary system, Al₂O₃-CaO-MgO-SiO₂. Supplement 2
focuses on the measurements of some $\text{Al}_2\text{O}_3$-$\text{CaO}$-$\text{MgO}$-$\text{SiO}_2$ slags in the temperature range 1773 K to 1923 K. The reliability of a dynamic thermal model necessitates reliable thermal conductivity data for ladle slag.

As a part of the project to describe the thermal state of a steel making ladle during the whole steelmaking process chain, the purpose of Supplement 3 and Supplement 4 was to develop a dynamic model for the preheating process and the teeming ladle, respectively.

In the preheating model the ladle wall temperature distribution and the dynamic gas flow inside the ladle during the preheating process are predicted. The model was developed in two dimensions. Measurements using an IR camera inside and outside of an industrial ladle have been carried out to verify the model calculation. Investigations in a laboratory have been made to measure the emissivities of the ladle inner wall lining.

The teeming ladle model predicts dynamically the flow fields in both the liquid phase and the gas phase along with the movement of the liquid upper surface. The model also predicts the temperature distributions in the liquid metal, the gas phase and all layers in the ladle wall. Temperature measurements using an infrared camera (IR) have been conducted on industrial steel ladles in operation in order to validate the model calculations. The emissivities of the outer wall of several industrial ladles were investigated.

Because of the lack of data for thermal conductivity, the slag layer on the top surface of the melt inside the ladle was neglected in Supplement 4. Since the newly determined thermal conductivities in Supplement 2 enable a reasonable consideration of the slag layer in the mathematical modelling, a remodelling of the velocity field and temperature distribution in the ladle as functions of time was carried out in Supplement 5.
2. EXPERIMENTAL WORK AND MODELLING

2.1 Thermal Conductivity Measurements

Determinations of the conditions for using the transient hot-wire method for slag systems were made. To reach this goal, CFD calculations and cold model experiments were conducted to determine the optimal experimental conditions. High temperature test measurements were made to examine the reproducibility of the technique and the suitability of the refractory materials. Lastly, the thermal conductivities of four different slag compositions from the \( \text{Al}_2\text{O}_3-\text{CaO-MgO-SiO}_2 \) system in the high CaO region were measured.

2.1.1 Determination of Experimental Conditions for Hot Wire Method

**Mathematical modelling.** To evaluate the use of the hot wire method for high temperature applications a mathematical model was developed using the commercial software package COMSOL Multiphysics 4.2a. The purpose of the modelling effort was to find the optimal dimensions of the crucible, wire position and the effect of the surface cooling in order to minimize natural convection. Calculations with different dimensions of the crucible, wire positions and surface boundary conditions were carried out.

In order to simulate the hot wire measurement process, the turbulent flow application and the joule heating application in COMSOL were used. To study the fluid flow driven by buoyancy forces due to the density difference, a three dimensional model was constructed. The continuity equation, momentum equations and energy conservation equation were solved simultaneously. The initial temperature of the liquid and the wire was set to 303 K. The initial velocity of the liquid was set to zero. The mesh was set as a compromise between convergence and memory requirement and can slightly differ within the calculations. The default solver provided by the software package was used.

To simplify the model, only the liquid domain (Figure 1) was modelled and the effect of the hot wire heated by joule heating was taken into consideration. The other parts of the circuit, the heat transfer to the crucible wall and surrounding was neglected. Only the heat transfer in the liquid and the resulting natural convection by the heating of the wire was of major interest. The heat transfer from the top of the crucible to the surrounding, however, was taken in consideration. A more detailed description of the model is given in Supplement 1.
Figure 1. Sketch of the modelling domain.

Measurements. The measurements at room temperature were carried out using a thermal state water bath. An illustration of the setup is given in Figure 2a. The whole measurement circuit (excluding the exposed hot wire) was sheathed in alumina tubes to avoid accidental contact between the wires and for insulation to minimize heat flux to the liquid. For the hot wire, Pt-10%Rh with a diameter of 0.35 mm and Pt-6%Rh with a diameter of 0.25 mm wire material was used. The liquid was Rhodosil Silicon Oil 550. The liquid was chosen because of its similar viscosity to slag.
The experiments were performed in the following manner: The thermal state water bath was heated up to 303 K. The crucible with the silicon oil was placed in the water bath for several hours to ensure the silicon oil had an exact temperature of 303 K. The hot wire was placed inside the crucible 10 minutes before measurement to make sure silicon oil was completely still after the movement of the wire. The measurement was carried out for 30 s. After the measurement, the wire was removed from the liquid for 10 minutes for cool down to eliminate residual heat left which could influence the next measurement. All the measurements were performed in this way. Figure 3 shows a typical example of a measurement curve, where the measured voltage change was plotted as function of $ln(t)$. The straight part of the curve was fitted using a simple linear regression. Only the slope $dV/dln(t)$ of the linear part of the curve can be used for the calculation of the thermal conductivity value.

**Figure 2.** Sketch of the a) low temperature experimental setup b) high temperature experimental setup.
To be able to calculate the thermal conductivity, the resistivity and the temperature coefficient of resistance of the wire need to be known. Therefore, resistivity measurements for the Pt-10\%Rh and Pt-6\%Rh wire were performed in the temperature range 298 K - 313 K at every 5 K. The calculated resistivity curve for the Pt-10\%Rh wire is given in **Figure 4**. Figure 4 shows the resistivity curve as a function of $\Delta T$.

**Figure 3.** Example of the line fitting; low temperature measurement, t is in second.

**Figure 4.** Cold model wire resistivity curve, wire diameter 0.35 mm.
The figure also shows the line fitting. From the line fitting, the resistivity $\rho_T$ of the wire at each measured temperature and the first order coefficient of resistance $\alpha$ were derived.

A sketch of the setup used in high temperature thermal conductivity measurements is given in Figure 2b. The setup was constructed to give the best performance for high temperature thermal conductivity measurements in a protective atmosphere. A furnace equipped with Kanthal Super heating elements up to 2023 K was used. The reaction tube, made of alumina, was sealed on the ends to avoid infiltration by oxygen. Argon was used as protection gas. The crucible dimensions were chosen based on the simulations and the cold model experiments, where it was found that the effect of convection in a crucible with smaller diameter is negligible. An inner diameter of 35 mm was chosen as a compromise between setup construction, measuring procedure and minimized convection.

The temperature in the reaction tube was controlled by a type C thermocouple, mounted in the crucible holder made of molybdenum, directly positioned under the crucible as shown in Figure 2b. As insulation material hafnia (HfO$_2$) was chosen instead of more commonly used hard-fired alumina since it does not appreciably dissolve in the slag composition that was studied.

By measuring and calculating the resistivity and the first and second order temperature coefficient of resistance of the hot wire in the temperature range suitable for measurements, any wire material could theoretically be used to perform the measurements. However, for high temperature thermal conductivity measurements of slag, the choice of materials is strictly limited, since firstly the material has to withstand the high temperatures, and secondly the material has to be resistant to corrosion by the aggressive melt. For these measurements Pt-30%Rh wire was chosen because of its higher melting point (around 2200 K) and it was found by trial and error that the higher the amount of rhodium in the wire, the longer the wire can withstand SiO$_2$. This means a higher amount of rhodium in the wire or a pure rhodium wire would be more suitable for measuring the thermal conductivity in high silicate slags (more than 40% SiO$_2$). A schematic of the high temperature measurement cell is given in Figure 5.
The instrumentation for the high-temperature measurements were the same as used in low-temperature measurements. The measurements were performed in the following way. The crucible with slag was placed in the furnace with the top surface of the slag at the hottest point. The furnace was heated up to the temperature which was suitable for the measurement and kept there for at least one hour to make sure the slag had a uniform temperature distribution. The hot wire was submerged in the melt for one minute before actual measurement to make sure the wire had the same temperature as the slag. The measurement was carried out for 15 s. After the measurement the wire was taken out of the melt for 15 minutes to eliminate residual heat left which would affect the next measurement. All the measurements were performed in this manner. A typical example of the measurement curve for temperature measurements is given in Figure 6, where the voltage change was plotted as a function of $\ln(t)$. Only the slope $dV/d\ln t$ of the straight line fitted part of the curve can be used for the calculation of the thermal conductivity value.
As already mentioned above for the cold model measurements, in order to calculate the thermal conductivity it is necessary to measure the resistivity of the wire, where the temperature coefficient of resistance of the hot wire can be calculated. The calculated resistivity curve for the Pt-30%Rh wire is given in Figure 7. This figure shows the resistivity curve as a function of $\Delta T$. The figure also shows the line fitting curve. From the line fitting curve the resistivity $\rho_T$ of the wire at 1773 K, 1823 K, 1873 K and 1923 K and the first and second order coefficient of resistance $\alpha$ and $\beta$ can be derived.

**Figure 6.** Example of the line fitting; high temperature measurement, t is in second.

**Figure 7.** High temperature wire resistivity curve, wire diameter 0.25 mm.
For better understanding and proof of reproducibility the thermal conductivity of a slag with a composition of 38\%CaO-32\%Al_2O_3-20\%SiO_2-9\%MgO (analysed in mass\%) was measured. The thermal conductivity of the slag was measured at 1773 K, 1823 K, 1873 K and 1923 K. In the first measurement cycle the conductivity was measured from the lowest to the highest temperature, whereas in the second cycle from the highest to the lowest temperature. At each temperature three measurements were performed. The two measurement cycles were completely independent of each other. The cold model and high temperature measurement practice is described in detail in Supplement 1.

2.1.2 High Temperature Thermal Conductivity Measurements of Ladle Slag

Thermal conductivity measurements for four different slag compositions (Table 1) where carried out. Figure 2b shows a sketch of the high temperature experimental setup. A sketch of the measuring cell is given in Figure 5. A short description how the thermal conductivity measurements were performed can be found in the previous chapter. A more detailed explanation is given in Supplement 1 and Supplement 2.

Table 1. Analyzed slag compositions.

<table>
<thead>
<tr>
<th>Analyzed Composition of the Al_2O_3-CaO-SiO_2-MgO System [Mass %]</th>
<th>Slag 1</th>
<th>Slag 2</th>
<th>Slag 3</th>
<th>Slag 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>32/38/20/9</td>
<td>34/39/18/9</td>
<td>34/45/14/7</td>
<td>43/43/9/5</td>
</tr>
</tbody>
</table>

2.2 Ladle Preheating

Measurements of temperature were carried out on a steelmaking ladle during the preheating process. Laboratory measurements were performed to investigate the emissivity of the ladle inner working lining. To predict the temperature distribution in the ladle walls during the preheating process, a two dimensional dynamic model was developed. The measured temperatures and investigated emissivities were used for model verification and as input parameters.

2.2.1 Laboratory and Industrial Measurements

As model input parameters and for temperature measurements using an infrared (IR) camera the emissivity of the inner ladle lining needs to be known. The value of the inner lining depends strongly on surface condition and material. To tackle this situation, the emissivities of two different samples were measured in the laboratory; namely a sample of used side wall brick with a slag layer on the surface, and a sample of a single slag layer. The measurements were performed according to the following steps:

1. The samples were heated up to 673 K and kept at this temperature for more than one hour to make sure the temperature distribution being uniform in the whole sample.
(2) The exact temperature of the sample was recorded at the instance the furnace door was opened. Two IR images were taken, after few seconds of waiting time. The waiting time was introduced to have a small temperature gradient inside the furnace to be able to image the sample surface.

(3) In the next step the sample was heated up to 873 K and kept at this temperature for at least one hour. Afterwards the IR images were taken as described in the second step.

(4) The measurements were also made at 1073 K and 1273 K.

For model verification, measurements of temperature of both the inside and outside of a ladle were performed using a hand held infrared (IR) camera, model Flir ThermaCAM P65. The measured ladles were identical in size, having a capacity to hold 215 tons of liquid steel. The side wall of the ladle consisted of five layers and the bottom of three layers. The shape and the dimensions of the ladle are shown in Figure 8. The areas where the measurements are conducted are marked with IRAvg_S and IRAvg_B.

Figure 8. A schematic illustration of the ladle.
For the heat flux calculations from the outer surface to the surroundings, the ambient temperature was of great importance. The temperature was measured approximately five meters from the ladle using a thermocouple of type K. A more detailed explanation how the different measurements were performed is given in Supplement 3.

2.2.2 Preheating Burner Model

The domain of the calculation is schematically shown in Figure 9. The domain is based on the steelmaking ladle used for temperature measurements. The figure represents the ladle in two dimensions, where the side wall is comprised of five layers and the bottom wall of three layers. The domain of the model consists of three different subdomains, namely the solid phase, the gas phase and the flame.

![Figure 9](image.png)

**Figure 9.** Calculation domain and view factors.

The solid phase refers to the side wall, the bottom wall and the lid of the ladle, where the energy is transferred by conduction. The energy transport by conduction is governed by the
energy conservation equation. At the interface between solid wall and gas phase inside the ladle, the temperature of the wall was assumed to be the same as in the gas phase. To take into account the radiation from wall to wall inside the ladle, a surface-to-surface boundary condition on the inner ladle wall was introduced.

The gas phase refers to the gas inside the ladle during the preheating process. The energy is transported by convection and conduction. The transport is governed by the continuity, momentum and energy conservation equations for compressible fluids. To simulate the turbulent flow, the $k$-$\varepsilon$ turbulence model was used.\[^{23}\] The no-slip condition at the solid wall was modelled by using a wall function. The wall function boundary condition described the thin region near the wall with high gradients in the flow variables.

At the gas-flame interface a symmetry boundary condition was applied in the simulation of the flow tangential to the boundary. In order to model the heat transfer a temperature boundary condition with surface to ambient radiation was applied at the gas-flame interface. This means that a constant temperature of the flame was assumed. The flame acts as a pure emitter that irradiates to an object. The used view factors for radiation in the calculation are given in Figure 9.\[^{24, 25}\] The flame emissivity $\varepsilon$ was set to 0.3.\[^{26}\] The temperature distribution of the burner flame is given in Figure 8 and Table 2. The distribution is based on IR images (Figure 10) taken from the real flame and according to another publication.\[^{27}\] In the simulation of the outflowing gas between the lid and ladle edge, an heat flux boundary condition was applied.

**Table 2.** Initial flame temperature distribution.

<table>
<thead>
<tr>
<th>Position</th>
<th>Temperature [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2773</td>
</tr>
<tr>
<td>II</td>
<td>2623</td>
</tr>
<tr>
<td>III</td>
<td>2423</td>
</tr>
<tr>
<td>IV</td>
<td>2273</td>
</tr>
<tr>
<td>V</td>
<td>1973</td>
</tr>
<tr>
<td>VI</td>
<td>1823</td>
</tr>
<tr>
<td>VII</td>
<td>1623</td>
</tr>
<tr>
<td>VIII</td>
<td>1473</td>
</tr>
</tbody>
</table>
The preheated air temperature for the combustion process is given in the burner manual\textsuperscript{[28]} to be higher than 1273 K. Thusly the initial air temperature inside the ladle was assumed to be 1273 K.

The preheating process of a steel making ladle involves conduction, convection, radiation and combustion. Therefore, simplifications and assumptions were needed for the mathematical formulation. The following assumptions and simplifications were made for the model:

1. Each of the layers of the ladle wall/bottom were considered as uniform; and the contacts between the layers were considered as ideal.
2. No detailed modelling attempt was made for the combustion. Instead, the temperature of the outer surface of the flame was given as a boundary condition. The shape of the flame is based on photographic images of the flame, while the temperature of the flame surface is based on IR images (see Figure 10). Note that both the flame shape and its surface temperature would involve certain uncertainties. This aspect will be discussed in the discussion part.
3. The heat loss from the outer surface of the ladle was modelled using an overall heat transfer coefficient, $h$, as described in Supplement 4. The same approach was also adopted for the bottom of the ladle.
4. In reality, two flames were actually present. In view that both flames are situated a short distance from the central line and the two flames operate alternatively, it was simplified to one flame in the centre operating continuously.

The commercial software package COMSOL Multiphysics 3.5a was utilized for the calculations. The mesh was chosen as a compromise between convergence and solver memory requirement. Therefore the mesh differs slightly from calculation to calculation. The PARADISO direct solver was used for solving linear algebraic system.

\textbf{Figure 10.} Images of the flame a) photographic image b) infrared image.
For simulation of the gas phase, it was assumed that air is the major gas in the ladle. The physical and material properties of air were taken from the COMSOL Multiphysics inbuilt material library. All equations were solved simultaneously. A more detailed explanation of the model is given in Supplement 3.

2.3 Teeming Ladle

In order to be able to develop a model to predict the temperature distributions in the liquid metal phase, in the gas phase and in the ladle side wall and bottom during teeming, reliable industrial data are essential. For this purpose, temperature measurements were performed on ladles during and after teeming at the caster operations in a steelmaking plant. The measured temperatures are used to confirm the model prediction.

2.3.1 Industrial Measurements

The surface temperatures of the outside in a predefined surface area marked as IRAvg in Figure 11 of the ladle were measured by using a stationary infrared camera (IR) with continuous recording. The camera was a Flir ThermoVision A320, which was calibrated just prior to the measurements. The temperature measurements on the inside wall of the ladle were performed using a handheld IR-camera, model Flir ThermaCAM P65. A comparison calibration was performed between the two cameras with good agreement.

Figure 11. A schematic illustration of the ladle.
Accurate emissivity values are crucial to obtain accurate temperature measurements. The emissivity value on the steel shell of the ladle was determined by performing calibration measurements on three different ladles. In order to determine the emissivity of the steel shell, small areas (15 x 40 cm$^2$) were painted with glossy black paint. This simulated a perfect black body with an emissivity of 1 and homogenous surface properties. Thermal images were captured from the painted and non-painted areas (just beside the painted area) and the emissivity of the non-painted areas could be estimated by the ratio between the intensity of the non-black area and the black body. Finally the average temperature was evaluated using the emissivity (0.98) of the shell of the ladle.

The heat transfer from the ladle to the surroundings occurs by radiation and convection. In view that the convection depends greatly on the surrounding situation of the ladle, these two components are considered together and an overall heat transfer coefficient is used to describe the heat transfer to the surroundings. For this purpose, the surrounding temperature was measured using a thermocouple type K at a distance of about 5 m from the ladle outer surface. The temperature was measured to be 298 ± 3 K.

The surface temperature of the refractory bricks on the inside of the ladle was measured by IR camera after the end of casting and the removal of the lid which took place typically 5 - 15 minutes after the ladle was empty.

2.3.2 Ladle Teeming Model

With the use of the commercial software package COMSOL Multiphysics 3.5a, a model was developed to predict the velocity field and temperature distribution in a teeming ladle. Solid and fluid domains were taken into consideration. The solid domains refer to the ladle bottom and side walls as well as the lid on the top of the ladle. The two fluid domains are liquid steel in the ladle and the gas phase on the top of the steel melt. In order to simulate the effect of the slag layer covering the liquid melt a conductive layer boundary condition at the gas liquid interface was introduced. The heat transfer by convection to the surroundings was predicted with use of a heat transfer coefficient.

The equation of continuity, the momentum equations and the energy equation were solved simultaneously. The modelling was performed for the ladles on which the temperature measurements were conducted. The calculating domain is schematically shown in Figure 12. The figure shows a two dimensional axisymmetric representation of the ladle with the five layered side wall and the three layered bottom. Inside the ladle, the gas phase is above the liquid steel surface. The interface between the liquid metal and gas moves downwards during casting. The boundary between gas and liquid shown in Figure 12 indicates the initial position of the interface and the slag layer on the top surface of the melt which follows the liquid steel.
The model consists of three sub models; namely (1) heat conduction through the ladle walls including the ladle lid, (2) heat transfer in the liquid metal, (3) heat transfer in the gas phase.

The solid phase refers to side wall, bottom wall and the lid. The heat transfer is governed by the energy equation for conduction. The temperature at the boundary between the inside wall and the liquid metal is assumed to be constant across the interface. An identical assumption approach is used above the steel liquid surface where the temperature at the boundary between the inside wall and the gas is assumed to be constant across the interface. This means the heat flux in the normal direction is continuous across the boundary. A heat transfer coefficient at the outside walls takes consideration of the heat flux \(q\) form the ladle to the surrounding (Figure 12).

The assumed initial temperature profiles for the side wall and bottom are shown in Figure 13. As can be seen from Figure 13 the initial profiles are close to a steady state status. The initial temperature of the lid is set to 973 K. The surrounding temperature, \(T_{\text{inf}}\), is based on measurements and is set to 298 K.
The liquid phase refers to the steel melt in the ladle (Figure 12). Fluid flow and heat transfer in this phase are governed by the continuity equation, momentum balance and energy balance. These conservation equations are given in cylindrical coordinates and can be easily found in any transport phenomena reference literature. In order to take the natural convection into consideration, these equations were solved simultaneously. The turbulent nature of the flow in the melt was modelled using the $k$-$\varepsilon$ turbulence model.\textsuperscript{[23]}

The boundary condition set at the central line was an axial symmetry which prescribed that there is no flux (including energy) in $r$ - direction and no stress in $z$ - direction. At the solid walls a logarithmic wall function was applied. This approach is usually adopted for high Reynolds numbers and situations where pressure variations along the wall are not very large. At the gas-melt interface it was assumed there was no penetration or shear stresses. The heat flux in the $z$ - direction is continuous across the boundary. The initial height of the liquid is 4.3 m. The molten steel is initially assumed uniform and the steel temperature is assumed to be 1823 K. The initial velocities are set to zero.

The gas phase refers to the air layer between the liquid steel surface and lid (Figure 12). The flow and heat transfer inside the gas phase are governed by the equations for continuity, momentum conservation and energy conservation for compressible fluids. The turbulent flow was modelled using the $k$-$\varepsilon$ turbulence model. All the equations were solved simultaneously in view of the strong dependence of gas density on temperature.

At the central line, as in the liquid phase, there was no flux (including energy) in $r$ - direction and no stress in the $z$ - direction. At the solid walls, as in the liquid phase, logarithmic wall function was applied. At the gas-melt interface it was assumed there is no penetration or shear stresses at the interface. The heat flux in the $z$ - direction was continuous across the boundary.
The initial air temperature inside the ladle was assumed to be the same as the liquid steel i.e. 1823 K. The initial velocities in the gas phase were set to zero.

In order to introduce the effect of the slag layer, a conductive boundary condition was set at the gas and liquid interface inside the ladle (Figure 12). The benefit of using this boundary condition is that it simulates a layer on the boundary instead of using an additional domain. Moreover, the required number of mesh elements can be reduced and the simulation time can be shortened. The thickness of the slag layer was initially set to 0.05 m. In the simulation, different values were employed for the thermal conductivity of the slag layer based on experimentally determined conductivities in Supplement 2.

The following assumptions were made for the model:

1. The slag layer on the top free surface of the ladle was introduced with use of a conductive layer boundary condition. Only the stationary heat conduction and the slag layer thickness were taken into consideration. The effect of the natural convection inside the slag layer and radiation to the ladle walls and lid was neglected.
2. In industrial practice, there is a gap between the lid and ladle wall. This gap was neglected. It was assumed that the lid closes perfectly and the heat was only transferred by conduction through the lid.
3. The thickness of the ladle wall was considered as corresponding to a new ladle.
4. No surface to surface radiation was taken into account.
5. Perfect conduction between the different wall layers was assumed. It was also assumed that all the different phases were homogenous in composition.
6. The effect of the teeming hole, porous plugs and filling materials on the heat transfer and fluid flow was very small and therefore was not taken in consideration.

In order to study the effect of slag layer, calculations both with and without slag layer were conducted. In the case with a slag layer, the thermal conductivity of the slag was set to 0.05 W·m⁻¹·K⁻¹ assuming that the melt was covered with liquid layer of the slag with the lowest measured thermal conductivity (Supplement 2). It is reported in Supplement 2 that the presence of a solid phase increases the thermal conductivity considerably. To examine the effect of precipitation of solid oxide on ladle thermal state, calculation using the thermal conductivities of 0.3 W·m⁻¹·K⁻¹ and 1.0 W·m⁻¹·K⁻¹ (corresponding to complete solid oxide layer) were carried out.

The commercial software package COMSOL Multiphysics 3.5a was utilized for the calculations. In order to simulate the movement of the gas-melt interface and the slag layer, the Moving Mesh (ALE) application mode was employed. The moving mesh velocity at the gas-melt/slag layer interface in the negative z - direction was adapted to the two industrial cases studied. For Ladle A the sinking rate of the steel surface was set to -1.2·10⁻³ m·s⁻¹ and for Ladle B to -8.3·10⁻⁴ m·s⁻¹, respectively. The total teeming time for Ladle A was 3572 s and 5150 s for Ladle B.
3. RESULTS

3.1. Thermal Conductivity Measurements

The experimental conditions for the transient hot wire method for metallurgical slags at steelmaking temperatures were determined and applied to high temperature thermal conductivity measurements. The measurements were carried out on different slag compositions. The results are presented in this chapter.

3.1.1 Determination of Experimental Conditions for Hot Wire Method

**Modelling results.** Figure 14 shows the velocity field caused by natural convection as a function of the crucible diameter at 15 s simulation time. For all the different crucible diameters the velocity after 15 s simulation time is very low, where the highest maximum velocity is 0.24 mm·s⁻¹ in the crucible with the largest diameter 8.81 mm. The lowest maximum velocity 0.21 mm·s⁻¹ is related to the crucible with the smallest diameter 3.8 mm. Thus, it is evident that the larger the diameter of the crucible, the higher the maximum velocity caused by natural convection.
Figure 14. Velocity magnitude as a function of crucible diameter a) $d = 8.81$ mm b) $d = 6.7$ mm c) $d = 5.1$ mm d) $d = 3.8$ mm.

Figure 15 shows the velocity field from natural convection after 15 s simulation time. The velocity field is given as a function of the wire position. Figure 15 clearly shows that the velocity is slightly higher (0.016 mm·s$^{-1}$) when the wire is out of centre.
Figure 15. Velocity magnitude as a function of wire position a) middle b) out of centre c) top d) bottom.

Figure 16 shows the velocity field as a function of the surface cooling on the top of the crucible. The boundary in Figure 16a was set to convective cooling. The heat transfer coefficient used was the built-in COMSOL heat transfer coefficient for air. The reference temperature was set to 298 K. In Figure 16b the boundary on the top of the crucible was set to thermal insulation. As Figure 16a and 16b show, after 15 s simulation time there is no difference in the velocity field. At 303 K the cooling on the surface does not seem to have any influence on the velocity field in the liquid.
Figure 16. Velocity magnitude as a function of the top surface cooling a) boundary set to convective cooling b) boundary set to thermal insulation.

Figure 17 shows the velocity field caused by natural convection for the crucible with a diameter of 3.8 mm as a function of time. After 1 second simulation time (Figure 17a) the maximum velocity is 0.018 mm·s⁻¹ and after 300 s simulation time (Figure 17b) the velocity is 1.1 mm·s⁻¹.
Figure 17. Velocity magnitude as a function of simulation time a) at 1 s b) at 50 s c) at 150 s d) at 300 s.

Figure 18 shows the effect of the natural convection in the crucible on the maximum temperature of the wire as a function of simulation time. Figure 18a gives the maximum temperature profile of the wire without convection effect for 300 s. For this simulation only the conduction was considered and the wire was placed exactly in the middle of the crucible. From the figure it can be seen that the temperature increase of the wire is very high in the beginning. After approximately 10 s the temperature of the wire still increases, but not as fast as at the start. After 300 s simulation time the wire temperature still has not reached steady-state status.
Figure 18. Effect of natural convection on the maximum temperature of the wire as a function of time a) without convection, wire in the middle of the crucible b) with convection, wire in the middle of the crucible c) with convection, wire out of centre of the crucible.

Figure 18b shows the maximum wire temperature with effect of conduction and convection. The wire was placed exactly in the middle of the crucible. Up to a temperature of 328 K the curve is quite similar to the curve simulated without convection. The effect of convection becomes significant after approximately 50 s simulation time. Then the temperature of the wire decreases through cooling by natural convection. The effect on the temperature of the wire placed off-centre in the crucible is shown in Figure 18c. For this simulation, conduction and convection were taken in consideration. The graph in Figure 18c differs slightly from the one in Figure 18b. The part of the curve in the beginning is almost the same as shown in Figure 18a and 18b. The reached maximum temperature at 50 s simulation time differs slightly from Figure 18b.

Cold model experimental results. Table 3 lists the thermal conductivity values calculated from measurements for two different wire diameters and four different crucible sizes. All measurements were made at 303 K and for all measurements a constant current of 1.53 A was measured.

Table 3. Calculated thermal conductivity from cold model measurements at 303 K at different diameters of crucible and wire.

<table>
<thead>
<tr>
<th>Crucible Diameter [mm]</th>
<th>Measured Source Current [A]</th>
<th>Thermal Conductivity $d_{wire} = 0.25$ mm [W·m$^{-1}$·K$^{-1}$]</th>
<th>Thermal Conductivity $d_{wire} = 0.35$ mm [W·m$^{-1}$·K$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>1.53</td>
<td>0.24</td>
<td>0.17</td>
</tr>
<tr>
<td>38</td>
<td>1.53</td>
<td>0.25</td>
<td>0.15</td>
</tr>
<tr>
<td>51</td>
<td>1.53</td>
<td>0.20</td>
<td>0.16</td>
</tr>
<tr>
<td>51</td>
<td>1.53</td>
<td>0.26</td>
<td>0.16</td>
</tr>
<tr>
<td>67</td>
<td>1.53</td>
<td>0.21</td>
<td>0.17</td>
</tr>
<tr>
<td>67</td>
<td>1.53</td>
<td>0.19</td>
<td>0.15</td>
</tr>
<tr>
<td>88</td>
<td>1.53</td>
<td>0.20</td>
<td>0.15</td>
</tr>
<tr>
<td>88</td>
<td>1.53</td>
<td>0.24</td>
<td>0.18</td>
</tr>
</tbody>
</table>
Table 4 gives the thermal conductivity values calculated from cold model measurements as a function of the position of the wire. All measurements were taken at 303 K and for all measurements a constant current of 1.53 A was measured. For these measurements only the Pt-10%Rh wire with a diameter of 0.35 mm was used.

Table 4. Calculated thermal conductivity from cold model measurements at 303 K at different positions of the wire.

<table>
<thead>
<tr>
<th>Crucible Diameter [mm]</th>
<th>Measured Source Current [A]</th>
<th>Wire Material</th>
<th>Wire Position</th>
<th>Thermal Conductivity $d_{wire} = 0.35$ mm $[\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>1.53</td>
<td>Pt-10%Rh</td>
<td>top</td>
<td>0.15</td>
</tr>
<tr>
<td>38</td>
<td>1.53</td>
<td>Pt-10%Rh</td>
<td>top</td>
<td>0.16</td>
</tr>
<tr>
<td>38</td>
<td>1.53</td>
<td>Pt-10%Rh</td>
<td>centre</td>
<td>0.17</td>
</tr>
<tr>
<td>38</td>
<td>1.53</td>
<td>Pt-10%Rh</td>
<td>centre</td>
<td>0.15</td>
</tr>
<tr>
<td>38</td>
<td>1.53</td>
<td>Pt-10%Rh</td>
<td>bottom</td>
<td>0.14</td>
</tr>
<tr>
<td>38</td>
<td>1.53</td>
<td>Pt-10%Rh</td>
<td>bottom</td>
<td>0.17</td>
</tr>
<tr>
<td>38</td>
<td>1.53</td>
<td>Pt-10%Rh</td>
<td>off-centre</td>
<td>0.15</td>
</tr>
<tr>
<td>38</td>
<td>1.53</td>
<td>Pt-10%Rh</td>
<td>off-centre</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 5 gives the thermal conductivity values calculated from the cold model measurements as a function of the source current. For all measurements the Pt-10%Rh wire with a diameter of 0.35 mm was used. The measurements were conducted at 303 K. The lowest measured source current was 1.03 A and the highest measured source current was 3.53 A.

Table 5. Calculated thermal conductivity from cold model measurements at 303 K at different source current.

<table>
<thead>
<tr>
<th>Crucible Diameter [mm]</th>
<th>Wire Diameter [mm]</th>
<th>Wire Material</th>
<th>Measured Source Current [A]</th>
<th>Thermal Conductivity $d_{wire} = 0.35$ mm $[\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>0.35</td>
<td>Pt-10%Rh</td>
<td>1.03</td>
<td>0.17</td>
</tr>
<tr>
<td>38</td>
<td>0.35</td>
<td>Pt-10%Rh</td>
<td>1.03</td>
<td>0.18</td>
</tr>
<tr>
<td>38</td>
<td>0.35</td>
<td>Pt-10%Rh</td>
<td>1.53</td>
<td>0.17</td>
</tr>
<tr>
<td>38</td>
<td>0.35</td>
<td>Pt-10%Rh</td>
<td>1.53</td>
<td>0.15</td>
</tr>
<tr>
<td>38</td>
<td>0.35</td>
<td>Pt-10%Rh</td>
<td>2.03</td>
<td>0.14</td>
</tr>
<tr>
<td>38</td>
<td>0.35</td>
<td>Pt-10%Rh</td>
<td>2.03</td>
<td>0.16</td>
</tr>
<tr>
<td>38</td>
<td>0.35</td>
<td>Pt-10%Rh</td>
<td>2.53</td>
<td>0.13</td>
</tr>
<tr>
<td>38</td>
<td>0.35</td>
<td>Pt-10%Rh</td>
<td>2.53</td>
<td>0.14</td>
</tr>
<tr>
<td>38</td>
<td>0.35</td>
<td>Pt-10%Rh</td>
<td>3.03</td>
<td>0.14</td>
</tr>
<tr>
<td>38</td>
<td>0.35</td>
<td>Pt-10%Rh</td>
<td>3.03</td>
<td>0.15</td>
</tr>
<tr>
<td>38</td>
<td>0.35</td>
<td>Pt-10%Rh</td>
<td>3.53</td>
<td>0.15</td>
</tr>
<tr>
<td>38</td>
<td>0.35</td>
<td>Pt-10%Rh</td>
<td>3.53</td>
<td>0.13</td>
</tr>
</tbody>
</table>
**High temperature experimental results.** Some investigations were done on the performance of the sheathing material. The results are given in **Figure 19**. Figure 19 shows the difference in dissolution between $\text{Al}_2\text{O}_3$ and $\text{HfO}_2$. The diameters of the alumina and hafnia cover tubes are shown before and after measurements. The hard-fired alumina tube was used for five and the hafnia tube for more than 60 measurements.

![Image](image1)

**Figure 19.** Insulation sheaths a) comparison of the diameters between new and used insulation sheaths b) cross-section of the used sheaths.

The calculated thermal conductivity values for the high temperature measurements are given in **Table 6**. The measurements were conducted at 1773 K, 1823 K, 1873 K and 1923 K. The measured slag composition after analysis is 38%CaO, 32%Al$_2$O$_3$, 20%SiO$_2$ and 9%MgO given in mass percentage. Two different measurement cycles were realized.


Table 6. Calculated thermal conductivity from high temperature measurements at different temperatures.

<table>
<thead>
<tr>
<th>Analysed Slag Composition [Mass %]</th>
<th>Temperature [K]</th>
<th>Thermal Conductivity [W·m⁻¹·K⁻¹]</th>
<th>Thermal Conductivity [W·m⁻¹·K⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>38%CaO-32%Al₂O₃-20%SiO₂-9%MgO</td>
<td>1773</td>
<td>0.162</td>
<td>0.179</td>
</tr>
<tr>
<td></td>
<td>1173</td>
<td>0.171</td>
<td>0.178</td>
</tr>
<tr>
<td></td>
<td>1173</td>
<td>0.180</td>
<td>0.177</td>
</tr>
<tr>
<td></td>
<td>1823</td>
<td>0.118</td>
<td>0.111</td>
</tr>
<tr>
<td></td>
<td>1823</td>
<td>0.111</td>
<td>0.110</td>
</tr>
<tr>
<td></td>
<td>1823</td>
<td>0.116</td>
<td>0.116</td>
</tr>
<tr>
<td></td>
<td>1873</td>
<td>0.064</td>
<td>0.061</td>
</tr>
<tr>
<td></td>
<td>1873</td>
<td>0.064</td>
<td>0.060</td>
</tr>
<tr>
<td></td>
<td>1873</td>
<td>0.060</td>
<td>0.063</td>
</tr>
<tr>
<td></td>
<td>1923</td>
<td>0.045</td>
<td>0.046</td>
</tr>
<tr>
<td></td>
<td>1923</td>
<td>0.047</td>
<td>0.035</td>
</tr>
<tr>
<td></td>
<td>1923</td>
<td>0.039</td>
<td>0.033</td>
</tr>
</tbody>
</table>

3.1.2 High Temperature Thermal Conductivity Measurements of Ladle Slag

Thermal conductivity values for four different slag compositions are given in Table 7. Note that measurements of three independent temperature cycles were conducted for each slag composition. For two slags, the three temperature cycles were made in the same experiments, while in the case of other two slags, the three cycles were carried out in different experiments. Despite this difference, the measured thermal conductivity data show very good reproducibility for all slag compositions and temperatures. Figure 20 presents the thermal conductivities as function of temperature of the four slags. Note that the plotted data are the average values of three measurements.
Table 7. Thermal conductivity values calculated from measurements for different temperatures and compositions.

<table>
<thead>
<tr>
<th>Analyzed Composition Al₂O₃-CaO-SiO₂-MgO System [Mass %]</th>
<th>Measurement cycle</th>
<th>Thermal Conductivity at 1773 K [W·m⁻¹·K⁻¹]</th>
<th>Thermal Conductivity at 1823 K [W·m⁻¹·K⁻¹]</th>
<th>Thermal Conductivity at 1873 K [W·m⁻¹·K⁻¹]</th>
<th>Thermal Conductivity at 1923 K [W·m⁻¹·K⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slag 1 32/38/20/9</td>
<td>1</td>
<td>0.179</td>
<td>0.111</td>
<td>0.061</td>
<td>0.046</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.178</td>
<td>0.110</td>
<td>0.060</td>
<td>0.035</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.177</td>
<td>0.116</td>
<td>0.063</td>
<td>0.033</td>
</tr>
<tr>
<td>Slag 2 34/39/18/9</td>
<td>4</td>
<td>-</td>
<td>0.044</td>
<td>0.038</td>
<td>0.029</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-</td>
<td>0.044</td>
<td>0.039</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-</td>
<td>0.050</td>
<td>0.041</td>
<td>0.029</td>
</tr>
<tr>
<td>Slag 3 34/45/14/7</td>
<td>7</td>
<td>-</td>
<td>0.048</td>
<td>0.046</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-</td>
<td>0.051</td>
<td>0.046</td>
<td>0.027</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>-</td>
<td>0.049</td>
<td>0.046</td>
<td>0.028</td>
</tr>
<tr>
<td>Slag 4 43/43/9/5</td>
<td>10</td>
<td>-</td>
<td>0.087</td>
<td>0.049</td>
<td>0.029</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>-</td>
<td>0.093</td>
<td>0.052</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>-</td>
<td>0.095</td>
<td>0.050</td>
<td>0.025</td>
</tr>
</tbody>
</table>

Figure 20. Thermal conductivity of ladle slag for different temperatures and compositions.

3.2 Ladle Preheating

Measurements of temperature were carried out on a ladle of a steel industry during the preheating process and laboratory measurements were performed to investigate the emissivity of the ladle inner working lining. To predict the temperature distribution in the walls of a ladle
during the preheating process, a two dimensional dynamic model was developed. The measurement and the modelling results are presented in this chapter.

3.2.1 Laboratory and Industrial Measurements

**Measurement results.** The measured temperatures and the calculated emissivity values are given in Table 8. It is seen in the table that the evaluated emissivity for the used side wall brick with a slag layer on the surface varies in a range of 0.79 to 0.84, while the calculated emissivity for the single slag layer is in the range of 0.82 to 0.88. An average value of the emissivity values for the wall brick covered by slag is calculated to be to $\varepsilon = 0.81$. In view that all the temperature measurements were made on the wall covered by slag, this value was used for the temperature measurements.

**Table 8.** Measured temperatures and calculated emissivity values.

<table>
<thead>
<tr>
<th>Predicted temperature [K]</th>
<th>Picture No.</th>
<th>Time after furnace start [h]</th>
<th>Thermocouple temperature measurement [K]</th>
<th>Calculated emissivity - Used side wall brick with slag ($\varepsilon$)</th>
<th>Thermocouple temperature measurement [K]</th>
<th>Calculated emissivity - Single slag layer ($\varepsilon$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>673 IR_1430</td>
<td>2:08</td>
<td>685</td>
<td>0.84</td>
<td>670</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>IR_1431</td>
<td>2:08</td>
<td>685</td>
<td>0.84</td>
<td>670</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>873 IR_1432</td>
<td>2:57</td>
<td>896</td>
<td>0.82</td>
<td>883</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>IR_1433</td>
<td>2:57</td>
<td>896</td>
<td>0.81</td>
<td>883</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>1073 IR_1434</td>
<td>4:26</td>
<td>1096</td>
<td>0.81</td>
<td>1088</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>IR_1435</td>
<td>4:26</td>
<td>1096</td>
<td>0.80</td>
<td>1088</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>1273 IR_1437</td>
<td>5:51</td>
<td>1273</td>
<td>0.79</td>
<td>1265</td>
<td>0.83</td>
<td></td>
</tr>
<tr>
<td>IR_1438</td>
<td>5:51</td>
<td>1273</td>
<td>0.79</td>
<td>1265</td>
<td>0.83</td>
<td></td>
</tr>
<tr>
<td>IR_1439</td>
<td>6:18</td>
<td>1273</td>
<td>0.81</td>
<td>1269</td>
<td>0.83</td>
<td></td>
</tr>
<tr>
<td>IR_1440</td>
<td>6:18</td>
<td>1273</td>
<td>0.80</td>
<td>1269</td>
<td>0.82</td>
<td></td>
</tr>
</tbody>
</table>

Since all available ladles were usually involved in the process chain, measurements had to be carried out in the gaps between the sub-processes. Measurements on two of the ladles were conducted. The results for the inside measurements are presented in Table 9. The start and end temperatures were measured. For Ladle A, the duration time was 4080 s and for Ladle B 3900 s. In the case of Ladle A, only the side wall temperature could be measured. For Ladle B, both the temperatures of the side wall and bottom could be measured. A comparison of the results in Table 9 reveals that though the average temperatures of the two studied ladles are slightly different at both start and end of the preheating process, the two ladles do not differ substantially. This almost negligible difference would somehow indicate the reliability of the measurements, as the two ladles have had very similar ladle history.
Table 9. Measured temperatures inside the ladle.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>IRAvg_S</td>
<td>4080</td>
<td>1136</td>
<td>1450</td>
<td>314</td>
<td>IRAvg_B</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>IRAvg_S</td>
<td>3900</td>
<td>1106</td>
<td>1430</td>
<td>324</td>
<td>IRAvg_B</td>
<td>1104</td>
<td>1429</td>
<td>325</td>
</tr>
</tbody>
</table>

The temperature measurements on the outer shell were conducted on the same ladles as the inside measurements. Also, the start and end temperatures were measured. The results are presented in Table 10. Table 10 also presents the measured surrounding air temperature for Ladle A and B.

Table 10. Measured temperatures at the outer surface of the ladle and surrounding.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4080</td>
<td>484</td>
<td>492</td>
<td>8</td>
<td>298</td>
</tr>
<tr>
<td>B</td>
<td>3900</td>
<td>531</td>
<td>514</td>
<td>-17</td>
<td>285</td>
</tr>
</tbody>
</table>

3.2.2 Modelling

As discussed in the industrial measurement section, the thermal status of Ladle A and Ladle B are very similar. In view that Ladle B has the data for both side wall and bottom, the model calculation was carried out only for Ladle B.

Figures 21a - 21c present the distributions of the gas velocity in the ladle at different moments of the preheating process. While the velocity distributions are very similar at different heating times, the velocity decreases in general with the preheating time. For example, the highest calculated velocity is $1.404 \text{ m} \cdot \text{s}^{-1}$ at 1000 s, and $1.345 \text{ m} \cdot \text{s}^{-1}$ at 3900 s.
Figure 21. Velocity distributions at different heating times - Ladle B a) 1000 s b) 1450 s c) 3900 s.

Figures 22a - 22c present the temperature distributions on the inner and outer surfaces of the ladle at different heating times. The figures show a continuous temperature increase on the inner surface and a decrease on the outer surface. At 3900 s the highest temperature on the inner surface is 1711 K and the lowest 1435 K. The lowest temperature on the outer surface is 487 K.

Figure 22. Temperature distributions at different heating times - Ladle B a) 1000 s b) 1450 s c) 3900 s.

Figures 23a - 23b present the temperature distributions in the side wall (23a) and the bottom (23b) at 3900 s. In both figures, thickness 0 stands for the outer surface of the wall. The calculations are made for three positions (SW1, SW2, SW3) on the side wall and three positions on the bottom (BW1, BW2 and BW3). These positions are marked in Figure 8.
3.3 Teeming Ladle

3.3.1 Industrial Measurements

The measured temperatures and the calculated emissivities of the outer shell are shown in Table 11. It is seen that the emissivity varies in a range of 0.97 - 0.99. The variation obtained is believed to be due to the variation in surface properties of the steel shell, e.g. dust layer.

Table 11. Measured temperatures and calculated emissivities of the outer shell.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>E (66)</td>
<td>IR_1447</td>
<td>352</td>
<td>351</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>IR_1448</td>
<td>353</td>
<td>352</td>
<td>0.99</td>
</tr>
<tr>
<td>D (63)</td>
<td>IR_1445</td>
<td>556</td>
<td>550</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>IR_1446</td>
<td>560</td>
<td>553</td>
<td>0.96</td>
</tr>
<tr>
<td>F (60)</td>
<td>IR_1441</td>
<td>550</td>
<td>548</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>IR_1442</td>
<td>549</td>
<td>547</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>IR_1443</td>
<td>547</td>
<td>546</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>IR_1444</td>
<td>550</td>
<td>547</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Temperature measurements were performed on five ladles during teeming. Figure 24 shows typical examples of the temperature-time curves recorded during teeming with an emissivity of \(\varepsilon = 0.98\). In Figure 24, Ladle A is on the 15th cycle and Ladle B on the 11th. It is interesting to note that the temperature of the outside steel shell increases with teeming time. The average temperatures at the surface of the ladles at the start and the end of the teeming are listed in Table 12. As shown in the table, a general increasing trend is observed for the temperature at the outer surface for all ladles. The inside surface temperatures of the Ladles A and B after teeming are presented in Table 13.
Figure 24. Measured and calculated average shell temperatures for ladle A (15 heat cycles) and B (11 heat cycles) ($\varepsilon = 0.98$ measurements, $h = 8.5 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ calculations).

Table 12. Average surface temperatures of the ladle shell measured by IR camera.

<table>
<thead>
<tr>
<th>Ladle No (Heats cycle)</th>
<th>Position</th>
<th>Casting time [s]</th>
<th>Start Temperature outside [K]</th>
<th>End Temperature outside [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (15) IRAvg</td>
<td></td>
<td>3572</td>
<td>553</td>
<td>569</td>
</tr>
<tr>
<td>B (11) IRAvg</td>
<td></td>
<td>5150</td>
<td>582</td>
<td>594</td>
</tr>
<tr>
<td>B (12) IRAvg</td>
<td></td>
<td>3152</td>
<td>602</td>
<td>605</td>
</tr>
<tr>
<td>C (29) IRAvg</td>
<td></td>
<td>4186</td>
<td>596</td>
<td>600</td>
</tr>
<tr>
<td>D (0) IRAvg</td>
<td></td>
<td>3110</td>
<td>545</td>
<td>572</td>
</tr>
</tbody>
</table>

Table 13. Calculated and measured temperatures on the inside of the ladle wall.

<table>
<thead>
<tr>
<th>Ladle (Heats)</th>
<th>Position</th>
<th>Time after Casting without lid [s]</th>
<th>Measured inside Temperature [K]</th>
<th>Calculated Temperature ($T_{inf} = 973 \text{ K}$) [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (15) IR01</td>
<td></td>
<td>300</td>
<td>1632</td>
<td>1617</td>
</tr>
<tr>
<td>B (11) IR01</td>
<td></td>
<td>300</td>
<td>1602</td>
<td>1619</td>
</tr>
</tbody>
</table>

3.3.2 Modelling

Figures 25a - 25c present the stream lines and velocity distributions in both gas phase and liquid phase at different teeming times. It is seen that the flow induced by the teeming along with natural convection can lead to a maximum velocity of $0.02 \text{ m} \cdot \text{s}^{-1}$ (z - direction) in the liquid. The natural convection in the gas phase is substantial. For example, the velocity in the gas phase can be as high as $0.4 \text{ m} \cdot \text{s}^{-1}$ (z - direction) after 3500 s. The strong convections will enhance the heat transfer in both the gas bulk and the liquid bulk.
Figures 25. Streamline and velocity distributions at different teeming times - Ladle A a) 1000 s b) 2250 s c) 3500 s.

Figures 26a - 26c present the temperature distributions in the ladle and at its outer wall at different teeming times. The figures indicate that a temperature decrease of 31 K can be expected in the steel between the start and the end of casting. At 1000 s, there is very little temperature gradient in the steel. On the other hand, the temperature gradient increases with teeming time. At 2250 s, the lowest temperature (1792 K) is found at the bottom in the centre of the bath. The largest temperature difference in the liquid steel at this time can be as high as 31 K. Considerable temperature gradients are noticed in the gas phase throughout the teeming process. It seems that the temperature gradient is even more pronounced at earlier stages of teeming.
In order to examine the effect of thermal conductivity of the slag on the velocity fields, the maximum velocities in ± z - direction calculated for different cases are presented in Table 14. The table reveals that there are no appreciable differences between the different cases.

Table 14. Maximum velocities in gas and liquid phase inside the ladle in ± z - direction as a function of teeming time and slag layer conductivity.

<table>
<thead>
<tr>
<th>Thermal Conductivity Slag Layer [W·m⁻¹·K⁻¹]</th>
<th>Phase</th>
<th>Max. Velocity at 1000 s Teeming Time in ± z - direction [m·s⁻¹]</th>
<th>Max. Velocity at 2250 s Teeming Time in ± z - direction [m·s⁻¹]</th>
<th>Max. Velocity at 3500 s Teeming Time in ± z - direction [m·s⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>no slag layer</td>
<td>Liquid</td>
<td>-0.022</td>
<td>-0.016</td>
<td>-0.018</td>
</tr>
<tr>
<td></td>
<td>Gas</td>
<td>0.57</td>
<td>-0.48</td>
<td>0.43</td>
</tr>
<tr>
<td>0.05</td>
<td>Liquid</td>
<td>-0.021</td>
<td>-0.021</td>
<td>-0.016</td>
</tr>
<tr>
<td></td>
<td>Gas</td>
<td>-0.29</td>
<td>0.49</td>
<td>0.51</td>
</tr>
<tr>
<td>0.3</td>
<td>Liquid</td>
<td>-0.021</td>
<td>-0.020</td>
<td>-0.016</td>
</tr>
<tr>
<td></td>
<td>Gas</td>
<td>0.30</td>
<td>0.43</td>
<td>0.46</td>
</tr>
<tr>
<td>1.0</td>
<td>Liquid</td>
<td>-0.021</td>
<td>-0.016</td>
<td>-0.018</td>
</tr>
<tr>
<td></td>
<td>Gas</td>
<td>-0.40</td>
<td>-0.46</td>
<td>0.43</td>
</tr>
</tbody>
</table>
Figure 27 shows the temperature distributions in the liquid and gas phases as well as in the side wall as a function of the teeming time. In the calculation, the slag layer between gas and liquid phase is taken into consideration. The thermal conductivity is taken as $0.05 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ and the thickness of the slag layer is 0.05 m.

![Temperature distributions at different teeming times including slag layer](image)

Figure 27. Temperature distributions at different teeming times including slag layer $k = 0.05 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ - Ladle A a) 1000 s b) 2250 s c) 3500 s.

In order to examine the effect of thermal conductivity of the slag on the temperature distribution, different thermal conductivities are used. As examples, the results calculated for the thermal conductivities, $0.3 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ and $1.0 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ are presented in Figures 28 and 29 respectively.
Figure 28. Temperature distributions at different teeming times including slag layer $k = 0.30 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ - Ladle A a) 1000 s b) 2250 s c) 3500 s.
Figure 29. Temperature distributions at different teeming times including slag layer
\( k = 1.0 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1} \) Ladle A a) 1000 s b) 2250 s c) 3500 s.

In the case with thermal conductivity at 0.3 W·m⁻¹·K⁻¹, the temperature in the liquid phase drops approximately 31 K from the beginning to the end of the teeming time. The highest observed temperature in the gas phase after 3500 s teeming time is 1589 K. In the case with thermal conductivity 1.0 W·m⁻¹·K⁻¹, the liquid temperature drops from the beginning of the teeming time to end from 1823 K to approximately 1792 K. The lowest and the highest temperatures in the gas phase after 3500 s teeming time are 1308 K and 1588 K.

4. DISCUSSION

4.1 Determination of Experimental Conditions for Hot Wire Method

According to the simulations, the crucible diameter for the high temperature experiments should be as small as possible in order to keep the natural convection as low as possible. The cold model measurements, however, do not show a better result for the smaller crucible diameter in comparison to the larger crucible diameter. The simulation shows that the velocity caused by natural convection at 15 s simulation time (Figure 14) even for the largest simulated crucible diameter (8.81 mm) is still very low (0.24 mm·s⁻¹). For the cold model thermal conductivity calculation only the measured values in the range between 2 till 4
seconds were taken in consideration. This means that the velocity of the natural convection is even lower than calculated in the simulation at 15 s simulation time. Therefore the influence on the thermal conductivity values calculated from measurements is negligible. This is why the cold model measurements show little difference between the different crucible diameters. In order to get closer to the real value during high temperature conductivity measurements, the crucible diameter was chosen to be as small as possible.

As seen from Table 3 the thickness of the wire has a much larger impact on the measured and calculated conductivity values. The calculated values from the measurements done with the 0.25 mm wire are approximately 1.5 times higher than the values calculated from the measurements with the 0.35 mm wire. The reason can be due to the explanation as follows: The heat generation for the thinner wire per surface area is 2.8 times higher than in the thicker wire, which means that the natural convection starts possibly much earlier than with the thicker wire. The values measured with the thicker wire are close to the value found in the literature\cite{29} for Rhodosil Silicon Oil 550 (0.14 W·m\(^{-1}\)·K\(^{-1}\)). The discrepancy between the real value and the measured and calculated values could be caused by the age and impurity of the silicon oil or the temperature distribution in the water bath. According to the results from the cold model measurements the thickness of the hot wire for the high temperature thermal conductivity measurements was chosen to be 0.25 mm. The wire thickness most commonly used for thermal conductivity slag measurement in literature\cite{16,17,20} is 0.15 mm. Since the results from our cold modelling show that a slightly thicker wire gives better measurement results the thickness of the wire was chosen as 0.25 mm. On the other hand, if the wire is too thick the heat generation per surface area is not enough to perform reasonable measurements. In some high temperature measurements, a wire with a thickness of 0.5 mm was used. Even with increasing current up to 3 A did not yield reasonable values.

According to the literature\cite{16,17,20} a source current from 1 A to 2 A is commonly used for the high temperature conductivity measurements. Table 5 gives the measured and calculated thermal conductivity values as a function of the source current. The values show the higher the current, the closer the thermal conductivity value to the one found in the literature. However, higher current means higher heat generation per surface area and therefore an increased risk of convection. Hence, 1.5 A was chosen as a suitable current level for the measurements as a compromise between accuracy and possible higher convection. A systematic and more detailed study might be required to further clarify the situation.

The effect of the placement of the wire in the crucible was studied in simulations (Figure 15) as well as in the cold model experiments (Table 4). In Figure 15, it is seen that the velocity and therefore the natural convection are slightly higher when the wire is placed out of centre in the crucible. The placement of the wire close to the top surface or bottom does not have a major effect. To show the effect of off-centre placement of the wire the maximum temperature of the wire was plotted over time (Figure 18c) in comparison to the perfect placement in the centre including convection (Figure 18b) and perfect placement in the centre excluding convection (Figure 18a). All three Figures 18a - 18c show that in the beginning the
temperature profiles look quite similar. This means if only the measurements in the first
seconds are used the effect of the off-centre placed wire on the conductivity values can be
neglected. The results of the cold model measurements and calculations given in Table 4
reinforce this conclusion.

A study on the insulation material for high temperature thermal conductivity measurements
was carried out (Figure19). Hafnia (HfO$_2$) was chosen instead of the more commonly used
hard-fired alumina since it does not dissolve appreciably in the slag compositions that were
studied. The diameter of the hard-fired alumina tube was reduced after five measurements
from 4.5 mm to 3.5 mm, whereas the hafnia tube did not show any reduction in diameter.
From Figure 19a it can be seen that the hafnia tube was only slightly covered by slag. Figure
19b shows the cross section of the used hard-fired alumina tube and the used hafnia tube with
use of an optical microscope. It can be seen in detail that some regions of the hard-fired
alumina tube already dissolved in slag. The figure of the hafnia tube reveals only some
penetration of the slag on the surface. This confirms that there is essentially no reaction
between slag and HfO$_2$.

4.2 High Temperature Thermal Conductivity Measurements of Slag

As seen in Figure 20, the thermal conductivity decreases with the increase of temperature
irrespective of the slag composition. At and above 1873 K, the thermal conductivities of the
four slags are very similar. On the other hand, the thermal conductivities of Slag 1 and 4 are
much higher than the other two slags at 1823 K. Slag 1 has a thermal conductivity as high as
0.18 W·m$^{-1}$·K$^{-1}$ at 1773 K. In contrast with Slag 1 and Slag 4, the thermal conductivities of
the other two slags do not increase substantially with the decrease of temperature. The
differences between these four slags could be explained by the precipitation of solid phase in
the two slags, namely Slag 1 and Slag 4 at lower temperatures. As revealed by the
Al$_2$O$_3$-CaO-SiO$_2$-MgO phase diagram$^{[30]}$, both Slag 1 and Slag 4 are in two-phase region at
and below 1823 K. Since solid oxide would have higher thermal conductivity, the presence of
solid particles in the liquid phase would increase the conductivity of the sample substantially.
It is interesting to see in Figure 20 that the conductivity of Slag 1 is about three times of the
value of Slag 2 and Slag 3, while they have very similar values when they are entirely in the
liquid phase.

It should be mentioned that the measured data in Table 7 show very good reproducibility, no
matter the slag being pure liquid or solid-liquid mixtures. The good reproducibility of the
thermal conductivity measurement along with the substantial increase of the conductivity in
the presence of solid phase might offer us some indirect but useful information regarding the
precipitation of solid particles (liquidus temperature?).

Both Figure 20 and Table 7 indicate that the pure liquid slags have very low thermal
conductivities, e.g. 0.044 - 0.051 W·m$^{-1}$·K$^{-1}$ at 1823 K. It is expected that the top slag would
act as a very good insulation layer during teeming, where convection in the slag is not
substantial. In the case of a two-phase mixture, the slag would not be as good of an insulator
as the pure liquid phase. It would be interesting and useful to study the insulation effect of the slag layer on ladle thermal state in future research. Even the effect of precipitation of solid oxide particles on thermal state needs further investigation.

4.3 Ladle Preheating

As seen in Figure 23b, the temperature distribution in the bottom does not depend on the position. This uniform temperature distribution can also been seen in Figures 22a - 22c. On the other hand, the temperature distribution in the side wall is dependent on the vertical position. While the temperature profiles at SW1 and SW2 are somewhat similar, the temperature distribution at SW3 differs substantially from the former two positions (Figure 23a). At SW3, the temperature gradient in the working lining is much more profound. Figure 23a also indicates that in the upper part of the ladle where the distance to the flame is very short, a much larger temperature increase with time is observed, the temperature on the surface increases from 1106 K to 1664 K. On the other hand the temperature increase in the lower region of the ladle is only 336 K. Note that the large temperature gradient in the working lining at the upper part of the ladle would pose a potential danger of thermal stress and therefore potential breakthrough of the lining. The temperature profiles shown in Figure 23a also imply that the energy loss from the liquid steel to the lining at lower positions is much higher.

Figure 23b shows that only the first 10 cm of the working lining is heated up to a higher temperature where the surface temperature reaches maximal 1464 K at 3900 s. Since only a few centimetres of the bottom are heated properly, a high energy loss from the liquid steel to the bottom wall could be expected.

In order to compare the measured temperatures with the model predictions, the average temperatures measured by IR thermography at the end of preheating are also included in Figure 22c. The calculated temperature distribution on the inner side wall surface (Figures 22a - 22c) is in good agreement with the measurements. The difference between the measured and calculated average temperature in the same area (IRAvg_S) is less than 20 K. The calculated average bottom temperature is 1462 K. The measured average temperature for the same area (IRAvg_B) is 1429 K. The difference in the bottom area is somewhat bigger than that in the side wall. Note that a skull of slag-steel mixture is left on the bottom of the ladle after casting and it is difficult to get an accurate emissivity reading for the skull. Nevertheless, in view of the inherent uncertainties of these types of measurements and the nature of the model, the model predictions could still be considered as reasonable.

The velocity field inside the ladle is driven by natural convection, which is caused by the density and pressure difference of the gas inside the ladle during the preheating process. The density and the pressure in the gas phase are strongly affected by the temperature change. During the preheating process the gas is heated by the energy provided by the flame and cooled down by the wall. Over time, the wall is heated and the convective driving force minimizes. This behaviour can be seen in Figures 21a - 21c. At 1000 s the surface
The temperature of the walls is lower and therefore the maximal velocity (1.404 m·s⁻¹) is higher. At 3900 s the surface is already heated up and therefore the velocity becomes lower. At a very long heating time with constant energy supply, the convection will almost stop, since ΔT becomes smaller and smaller. In reality the burner will shut down when the gas on the top of the ladle reaches a temperature of 1523 K. This is necessary to avoid overheating of the burner components. Hence, the system is far from reaching steady state before the heating is terminated.

Volkova et al.¹⁸ suggest on the basis of model calculation that the surface temperature distribution inside the ladle shows an increase from the top to the bottom. The present work reveals an opposite trend; viz. the temperature increasing from the bottom to the top. Note that Volkova et al.¹⁸ also suggest a much higher maximal velocity (6.6 - 8.5 m·s⁻¹) in the gas phase. These differences could be caused by many factors, such as different kind of burners and combustion ratio, different sizes, gases and so on.

The reducing thickness of the working lining on the ladle thermal status would be of interest to the steel producers. The present model is used to examine the effect of lining wearing in the preheating process. Two extreme cases are investigated. In the first case, a side wall thickness of 152 mm and bottom wall thickness of 250 mm is used to simulate a new ladle after relining. In the second case, a used ladle is simulated, in which, the working lining of both bottom and side wall is worn out (reduced by 72 mm). Figures 30a - 30b present the result after 5 h heating time. In comparison to the new ladle, the working lining and safety layers both have considerably higher temperatures. At the position SW3, the temperature increased about 162 K between safety and working lining. At the lowest position (SW1), the increase is even more, namely 181 K. The model calculations strongly suggest that a new ladle needs to be preheated for a considerably longer time.
Figure 30. Temperature distributions in the wall after 5 h heating time for different thicknesses of the working lining - a1) side wall 152 mm a2) bottom 250 mm b1) side wall 80 mm b2) bottom 178 mm.

The effect of the gap size between the lid and ladle on the preheating is also studied. Figures 31a - 31d present the temperature distributions for four different gap sizes (50 mm, 100 mm, 150 mm and 200 mm respectively) after heating for 3900 s. The figures show that the gap distance has only a small effect on the temperatures of the side wall and bottom. The temperature difference in the upper part of the ladle close to the flame is negligible, while small difference in the lower part of the ladle and the bottom is noticed. The largest temperature difference on the bottom is 9 K. In fact, the larger temperature difference in the lower part of the ladle is properly more related to the distance between flame and bottom than the distance between lid and ladle. The bigger the gap is, the bigger the distance is between the flame and the bottom.
As mentioned earlier, the shape of the flame was taken from photographic images (Figure 10a) and the temperature distribution of the flame was measured by IR images (Figure 10b). This simplification could lead to particular uncertainties. It was not possible to take photographic and IR images of the flame during the heating process of the ladle. Therefore the images of the flame were taken outside the ladle. Since the flame shape and temperature depend on combustion, pressure and convection, the shape and temperature outside of the ladle could be somewhat different. Another uncertainty could be introduced by the employed emissivity. The emissivity is not uniform in the whole flame, since it is related to the flame composition and combustion. A more deep study of the flame shape, temperature and emissivity would give a more accurate solution.
Another possible uncertainty in the present study is the emissivity value for the inner wall. The measurements were carried out using used side wall brick covered with slag. An average value \( \varepsilon = 0.81 \) was used for the determination of temperatures on the side wall. This value could only be treated as a rough approximation, since the surface texture inside the ladle could be very different. The slag might not cover the wall uniformly. This factor would introduce certain uncertainty in the temperature measurement. To improve the model, more studies on the emissivity of the different textures need to be carried out.

Despite the uncertainties mentioned above, the present model shows a reasonably good agreement with the measurements. In view of its simplicity, this approach could be easily used to model the preheating effect of a steel making ladle in industry.

### 4.4 Teeming Ladle

As seen in Figure 24, the temperature at the surface of the outside shell increases with teeming time. This implies that the heat transfer through the ladle wall, i.e. from the ladle inside to the outer surface of the steel shell, cannot be transferred equally fast from the surface of the steel shell to the surroundings. In view of the fact that the ladle is positioned in a location with little air convection on the outside of the ladle, this slow heat transfer is expected.

Figure 24 also shows the calculated temperature - time curve of Ladle A (15). A comparison of the experimental data with the model prediction indicates good agreement. As another example, the experimentally determined temperature - time curve and the calculated curve for Ladle B (11) are also compared in Figure 24. Again, good agreement between the model and the measurements is obtained.

As mentioned in the experimental part, it was not possible to measure the temperature inside the ladle directly after teeming due to practical constraints. Approximately five minutes after the ladle teeming, the inside wall temperature measurements could be performed. To handle the uncertainty introduced by this situation, the calculations were continued after teeming. The heat flux from the empty ladle without lid was simulated by assuming the radiation as the main heat transfer mechanism. It was expected that the air temperature above the ladle was about 973 K. The calculated temperatures at the position, where the measurement was made (IR01) are presented in Table 13. Despite the uncertainty of the air temperature, the calculated temperature of the inner surface of the wall compares reasonably well with the experimentally measured temperature. The agreements shown in Figure 24 and Table 13 suggest that the model simulates the heat transfer with an acceptable accuracy.

The effects of a number of parameters on the heat loss have been examined. Table 15 lists the predicted total energy loss through the side wall of the ladle to the surroundings during the teeming process.
Table 15. Total Energy loss from side wall to the surroundings.

<table>
<thead>
<tr>
<th>Heat Transfer Coefficient [W·m⁻²·K⁻¹]</th>
<th>Thickness of Working Lining [mm]</th>
<th>Highly Insulating Layer Conductivity (as shown in Table 3)</th>
<th>Energy Loss to the Surrounding Ladle A, 3750 s [J]</th>
<th>Energy Loss to the Surrounding Ladle B, 5150 s [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>h=7</td>
<td>152</td>
<td>normal</td>
<td>4.0·10⁸</td>
<td>6.4·10⁸</td>
</tr>
<tr>
<td>h=8.5</td>
<td>152</td>
<td>normal</td>
<td>4.8·10⁸</td>
<td>7.7·10⁸</td>
</tr>
<tr>
<td>h=9</td>
<td>152</td>
<td>normal</td>
<td>5.1·10⁸</td>
<td>8.1·10⁸</td>
</tr>
<tr>
<td>h=8.5</td>
<td>130</td>
<td>normal</td>
<td>4.8·10⁸</td>
<td>7.7·10⁸</td>
</tr>
<tr>
<td>h=8.5</td>
<td>70</td>
<td>normal</td>
<td>4.8·10⁸</td>
<td>7.7·10⁸</td>
</tr>
<tr>
<td>h=8.5</td>
<td>152</td>
<td>doubled</td>
<td>5.0·10⁸</td>
<td>8.0·10⁸</td>
</tr>
</tbody>
</table>

Table 15 clearly shows that a decrease of the working lining thickness has minimal effect on the overall energy loss to the surroundings. This is explained by the fact that the heat flux through the refractory layers is limited by the conduction of the insulating layers. An increase of the heat transfer (increase in $h$), i.e. a better heat transfer to the surroundings, increases the energy loss from the wall considerably.

The highly insulating layer needs special care. An unexpected compression due to thermal expansion or other mechanical forces in the ladle wall will lead to the increase of the thermal conductivity of the layer. As shown in Table 15, a doubled conductivity of this layer would result in considerable increase in the ladle heat loss.

As shown in Table 14, the maximum velocities in the gas phase and steel do not vary considerably, no matter whether slag is present or not. The results also indicate that the thermal conductivity has a very little impact on the velocity. A comparison of Figures 26, 27, 28 and 29 reveals that the top slag layer has a very little impact on the steel temperature. This observation is in accordance with the results given in Table 14.

The minor effect of slag layer on the distributions of velocity and temperature in the ladle is in contradiction to results of most of the previous works. This could be attributed to the lack of thermal conductivity data for the slag phase and the neglecting of gas phase in the previous model calculations.

The thermal conductivity of air (gas phase) at 1823 K is 0.09 W·m⁻¹·K⁻¹, which is very similar to that of slag (about 0.05). The similarity in thermal conductivity between air and slag leads to similar calculation results. Note that only conduction in the slag layer is considered and the total teeming time used in calculations is only 3572 s. During this short period, even the higher thermal conductivity of 1.0 W·m⁻¹·K⁻¹ has little effect on the result (Figure 29).

The present results suggest that the heat transfer through the gas phase plays an important role during ladle teeming. Since the gas phase has low velocity due to natural convection, it acts as a good insulator. The slag layer of about 0.05 m would not help to improve considerably the insulation. It should be mentioned that no natural convection in the slag phase is considered in
the model calculations. However, it would not affect the present discussion, since the convection would only enhance the heat transfer through the slag layer.

In this work the influence on the heat transfer by radiation inside the ladle is not investigated. In fact, surface to surface radiation occurs, e.g. radiation from the top surface of the slag layer to the upper side walls and lid of the ladle. The impact of radiation is expected to be insignificant, since the temperature differences between the slag layer, ladle upper side walls and lid are small. The lack of emissivity data of different materials is another main reason that the radiation was not included in the model. However, this aspect needs further investigation. The first step towards this investigation would be the determination of the emissivities of the slag.
5. SUMMARY

The optimal experimental conditions for applying transient hot-wire method to metallurgical slags at steelmaking temperatures were studied using the computational fluid dynamics (CFD) method, cold model experiments and high temperature test measurements. Thermal conductivities of four different ladle slags were measured. Very good reproducibility was obtained in the conductivity measurements of slag using the optimized conditions obtained in the present work.

A two dimensional model was developed to predict the temperature distribution of a steelmaking ladle during and after the preheating process. The fluid flow and heat transfer inside the ladle and the heat transfer in the different layers of the refractory were studied. The predicted temperatures were found to be in reasonable good agreement with the measured temperatures. It was found that the thicknesses of the working linings had significant influence on the temperature distribution and the heating time.

A two dimensional axisymmetric model was developed to predict the dynamic flow fields and temperature distributions in ladle during teeming. For the calculations an axisymmetric geometry of the ladle was utilised. The teeming process was simulated with a moving boundary between the gas and liquid phase. The slag layer was considered in a later stage as a stationary heat conduction boundary with a given thermal conductivity and slag layer thickness. The results show that the thickness of the working lining had no significant influence on heat transfer and fluid flow during teeming. The main focus for optimization should be on the surrounding temperatures and ambient conditions of the teeming ladle. The increasing conductivity of the highly conductive layer as a part of the ladle side wall had foremost impact on the heat loss and needs special care. It was found that the effect of the slag layer was insignificant. This could be explained by the following reason: The similarity in the thermal conductivity between air and slag led to similar calculation results; and the velocity in the gas phase was very low, and therefore the gas phase acted similar to slag as a good insulator.
6. REFERENCES


