Numerical and experimental investigation of heat and mass transfer of a concasting technology

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Abstract

The solidification and cooling of a continuously cast slab (generally a concasting) and simultaneous heating of the crystallizer is a very complicated problem of transient heat and mass transfer. The solving of such a problem is impossible without numerical models and experimental measurements of the temperature field, not only of the concasting itself, while it is being processed through the concasting machine (CCM), but of the crystallizer as well.

A three-dimensional (3D) numerical model of the temperature field of a CCM has been used. Simultaneously, together with the numerical computation, experimental research and measuring have to take place not only to be confronted with the numerical model, but also to make it more accurate throughout the course of the process.

The following parameters were measured on an actual CCM during production: Temperatures on the walls of the crystallizer, surface temperatures of the slab within the secondary cooling zone of the cage, the metallurgical length using radio-isotope methods. The cooling intensity of individual jets and radiation on the surface of the slab were conducted on the experimental laboratory device.

Experimental research enables the acquisition of data in real time which are necessary for the optimization. This will ensure the correct process procedure: real process $\rightarrow$ obtaining of input data $\rightarrow$ performing of the numerical analysis $\rightarrow$ optimization $\rightarrow$ correction of the real process. This linking procedure is very
important for the reaction to concrete actual conditions, mainly for the optimization.

This analysis was conducted using a program devised within the framework of the GA CR projects no. 106/98/0296, 106/01/1464, 106/01/1164 and 106/99/0728 of the EUREKA project EU-CONMOD 1867 and of the COST-OC.P3.20.

1 A 3D numerical model

The solidification and cooling of a concasting, and the simultaneous heating of the crystallizer, is, from the viewpoint of thermokinetics, a very complicated problem of transient heat and mass transfer. The investigation is practically impossible without the numerical simulation of the temperature field of the concasting and the crystallizer. The 3D transient temperature field of the concasting passing through the CCM—the zones of primary, secondary and tertiary cooling—can be described by the Fourier-Kirchhoff equation

$$\frac{\partial T}{\partial t} = \frac{k}{\rho \cdot c} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \left( \frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z} \right) \frac{Q_{\text{SOURCE}}}{\rho \cdot c}$$

(1)

After reaching the steady state, the derivative of the temperature by time is zero. Equation (1), considering movement in the direction of the z-axis only, can be simplified to

$$\frac{\partial T}{\partial t} = \frac{k}{\rho \cdot c} \Delta T + w \frac{\partial T}{\partial z} + \frac{Q_{\text{SOURCE}}}{\rho \cdot c}$$

(2)

Equation (2) includes the temperature field of a concasting in all its three phases: in the melt, in the mushy zone, and in the solid phase. Therefore the specific volume enthalpy $h_c = c \cdot \rho \cdot T$, which is dependent on temperature, is introduced. Equation (2) then takes on the form

$$\frac{\partial h}{\partial t} + w \frac{\partial h}{\partial z} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial T}{\partial z} \left( k \frac{\partial T}{\partial z} \right)$$

(3)

The specific heat capacity $c$, density $\rho$ and heat conductivity $k$ are also functions of temperature.

The 3D transient temperature field of the crystallizer, in which primary cooling takes place, is described by equation (2) without the members $w(\partial T/\partial z)$ and $Q_{\text{SOURCE}}/\rho \cdot c$. Figure 1 illustrates the thermal equilibrium of an elementary volume (general nodal point $i,j,k$). The introduced unitary heat conductivities, and heat flows in the directions of all main axes, are indicated here too. The unitary heat conductivity in the direction of the z-axis is described by

$$VZ_{i,j,k} = k(T) \frac{S_z}{\Delta z} \quad \text{or} \quad VZ_{i,j,k-1} = k(T) \frac{S_z}{\Delta z}$$

(4)
The heat flows through the general nodal point \((i,j,k)\) in the z-direction are described by the following equations

\[
\begin{align*}
\dot{Q}Z_{i,j} &= VZ_{i,j,k} \left( T_{i,j,k}^{(t)} - T_{i,j,k-1}^{(t)} \right) \\
\dot{Q}Z_{i,j} &= VZ_{i,j,k+1} \left( T_{i,j,k+1}^{(t)} - T_{i,j,k}^{(t)} \right)
\end{align*}
\] (5) (6)

The unknown temperature in the general nodal point of the crystallizer, in the course of a time step of \(\Delta t\), is expressed by

\[
T_{i,j,k}^{(t+\Delta t)} = T_{i,j,k}^{(t)} + (\dot{Q}Z_{i,j} + \dot{Q}Z_{i,j} + \dot{Q}Y_{i} + \dot{Q}Y_{i} + \dot{Q}X_{1} + \dot{Q}X) \frac{\Delta t}{c \Delta x \Delta y \Delta z}
\] (7)

where \(T_{i,j,k}^{(t)}\) is the temperature in the previous time.

The unknown enthalpy in the general nodal point of the concasting, in the course of the time step \(\Delta t\) is defined by

\[
h_{i,j,k}^{(t+\Delta t)} = h_{i,j,k}^{(t)} + (\dot{Q}Z_{i,j} + \dot{Q}Z_{i,j} + \dot{Q}Y_{i} + \dot{Q}Y_{i} + \dot{Q}X_{1} + \dot{Q}X) \frac{\Delta t}{c \Delta x \Delta y \Delta z}
\] (8)

where \(h_{i,j,k}^{(t)}\) is the enthalpy in the previous time.

The temperature of the general nodal point of the concasting is obtained from the functional enthalpy-temperature dependence. This function must be known for the relevant metallic material. The heat flow \(\dot{Q}Z_{i,j}\) in equation (8) is now given by the expression

\[
\dot{Q}Z_{i,j} = VZ_{i,j,k} \left( T_{i,j,k+1}^{(t)} - T_{i,j,k}^{(t)} \right) - VZ_{i,j,k} \Delta z \dot{w}h_{i,j,k}^{(t)}
\] (9)

The authors had chosen the explicit difference method, because it enables the application of the most convenient method of numerical simulation of the release

Figure 1 The thermal equilibrium diagram of a general nodal point of the network
Figure 2 Enthalpy as a Function of Temperature

of latent heat of phase or structural changes using the thermodynamic enthalpy function (Figure 2).

The susceptibility of the explicit method to oscillations in the numerical solution, due to an uncareful selection of temporal discretization (time step) is minimized by alternations of longer and shorter time steps. Another modification is one that evaluates the attained stationary state of the modeled process via three shorter time steps.

The numerical model must provide for the analysis of the temperature field of the concasting as it passes through the primary-, secondary- and tertiary-cooling zones, i.e. through the entire CCM. A software version of the model has been generated, enabling the analysis of the temperature field of the crystallizer, including the influence of its material, its cooling system, characteristics of the cooling medium, etc. The program takes into account the non-linearity of the task, i.e.:

- The dependence of the thermophysical properties of all materials entering the system being investigated.
- The dependence of the heat-transfer coefficients on all boundaries of the system on the temperature of the working surface (of the concasting and crystallizer) and on other influences (shift rate, intensity of spraying, etc.).

The system developed is capable of performing all necessary tasks—from the generation of the net, through the determination of the thermophysical properties and the definition of boundary conditions, to the numerical simulation of the temperature field.
2 The assignment and preparation for simulation

The described numerical model is prepared to investigate a radial CCM in any stage of the process, for example slab profiles $a \times b$, where $a$ is the width ranging from 800 to 1600 mm and $b$ is the thickness ranging from 120 to 250 mm.

![Diagram of coordinate system and slab dimensions]

$x$ - axis - index $i$ 0 to $m$ <25,50>
y - axis - index $j$ 0 to $n$ <25,50>
z - axis - index $k$ 0 to $m$ <500,1000>
$m \times n \times p$ 2 500 000 nodes

Figure 3 The numerical network and choice of the slab sizes

It was decided to simulate the temperature field of a 1530 x 250 mm steel slab. The conditions of pouring were characterized by the temperature in the tundish (1548°C), the temperature of the liquidus (1515°C), and the shift rate of the slab (0.71 m.min⁻¹).

The maximum number of nodal points is $2.5 \times 10^6$, which is sufficient even in cases when it is necessary to increase the network density in order to map greater changes in temperature (Figure 3). Such a density of the net enables linear interpolation of the temperatures among the points of the net, and also among the time sectors.

The automatic generation of the network is followed up by the setting of thermophysical material properties of the system being

![Diagram of measurement sensors]

Figure 4 Arrangement of measurement sensors
investigated, including their dependence on temperature. Their setting is possible either in the form of a table, or with the help of coefficients of approximation polynomials describing the curve. The following step is to determine the boundary conditions on all boundaries of the system. Even the dependence of heat transfer coefficients on temperature, and other operational parameters, have to be entered into the system. The definition of boundary conditions is the most difficult part of the investigation of the thermokinetics of the process. The boundary condition of the slab-crystallizer interface depends on the thermophysical properties, the state of the casting powder, and also on the shape of the gap.

The authors have, therefore, used a basic procedure for the analysis of the effect of boundary conditions on the accuracy of the model. The order of the significances of the coefficients on individual boundaries of the system has also been determined.

3 The experiment

Regarding the fact that on a real CCM (where there are many types of jets with various settings positioned inside a closed cage) it is practically impossible to conduct measurement of the real boundary conditions, a laboratory device had been introduced in order to measure the cooling characteristics of the jets. This laboratory device enables the measurement of each jet separately. It comprises a steel plate mounted with 18 thermocouples, heated by an external electric source. The steel plate is heated to the testing temperature, and then it is cooled by a cooling jet. On the return move the jet is covered by a deflector, which enables movement of the jet without cooling the surface.

Supportive measurements are conducted in the operation, as well as on the experimental laboratory device, which simulates the surface of a concast slab and allows measurement in certain points, especially under the jets. The numerical model of the temperature field of the slab is therefore continuously confronted with experimental analyses, and corrected.

![Figure 5 The temperature history of pyrometer](image)
The following parameters were (able to be) measured on an actual CCM during production:
- Temperatures on the walls of the crystallizer.
- Surface temperatures of the slab within the secondary-cooling zone.
- Surface temperatures upon exit from the secondary-cooling zone.
- The technological length using radio-isotope methods.

The following measurements had to be conducted on the experimental laboratory device:
- The cooling intensity of individual jets.
- Radiation on the surface of the slab.

Figure 4 illustrates the positions of 48 thermo-couples in two lines along all sides of the crystallizer. Another important area of the CCM is the zero section of the secondary-cooling zone, where the slab is cooled intensively by water jets from all sides. A total of 4 pyrometers were placed here (see Figure 4). Figure 5 illustrates the measured temperatures, together with statistical results. The numerical model serves also to determine the effect of radiation.

4 Determining the boundary conditions from experimentation

The heat transfer coefficients ($HTC$), between the surface passing through the slab and the working surface of the crystallizer, were determined from the measured temperatures in the walls of the crystallizer.

Upon exit from the crystallizer, there is only one, but extremely important $HTC$. This coefficient—on the outer surface of the slab—is dependent mainly on
The temperature of the surface, the shift rate and the intensity of cooling by spraying.

The laboratory device also allows the setting of the jet type, the flow of water, the air-pressure (of air-water jets), the distance between each jet and the investigated surface, the surface temperature and the shift rate. All of these jets had been measured individually on the actual laboratory device, which allows the measurement of temperatures beneath the surface within the slab, and which also simulates the movement of the slab.

Figure 7 The temperature field of the longitudinal section of the slab

Figure 8 The temperature history in the selected points of the cross-section
Based on the temperatures measured in dependence on time, the HTC's are calculated by an inverse task. They are then processed further using an expanded both numerical and an identification model, and converted to coefficients of the function \( HTC(T, y, z) \), which expresses the HTC in dependence on the surface temperature, and also on the position of the concasting with respect to the jet (Figure 6).

5 Numerical results

After the computation, it is possible to obtain the temperatures at each node of the network and at any time during the process. Figure 7 shows a 3D graph of the temperature field along the longitudinal section of the slab.

Very useful is the temperature history graph (Figure 8), which shows the temperature at defined points of the cross-section of the slab. The course of the temperatures can also be displayed in any other user-defined point.

Figures 7 and 8 illustrate the repetitive drops in temperature in the secondary-cooling zone, which are caused by the intensive cooling by jets. Each successive temporary increase in temperature, which is reflected in the saw-tooth character of the curve, is caused by the movement of the slab—the given point moves out of reach of the previous jet and passes through an unsprayed zone before it moves into the scope of the next jet in line.

The vertical shaded band in figure 8 shows the range of depths (17-17.625 m) beneath the level of the melt in the crystallizer, within which the slab becomes completely solid. The radio-isotope measurement confirmed this so-called metallurgical length to be 17.4 m.

Figure 9 shows a comparison of the computed and pyrometer-measured temperatures at a distance of 1000 mm beneath the level of the melt within the
crystallizer. The experimentally attained temperatures are marked by a band of ±25°C, which corresponds to the average dispersion. The fact that the computed values lie within the range of measured values proves that the model is appropriate.

6 Conclusions

Numerical simulation and experimental measurement together must be conducted on a real CCM and an experimental laboratory device. The similarity of the results attained from the computed and from the experimentally measured temperature field is very satisfactory.

Experimental research enables the acquisition of data in real time which are necessary for the optimization. This will ensure the correct process procedure: real process → obtaining of input data → performing of the numerical analysis → optimization → correction of the real process. This linking procedure is very important for the reaction to concrete actual conditions, mainly for the optimization.

This method is suitable for direct usage in facilities with the aim to analyze the given CCM and consequently to optimize, modernize, manage, reconstruct or to adapt for the change of the assortment of profiles, cast materials, feed speeds, etc.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
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<tbody>
<tr>
<td>c</td>
<td>specific heat capacity</td>
<td>[J. kg(^{-1}). K(^{-1})]</td>
</tr>
<tr>
<td>h</td>
<td>specific enthalpy</td>
<td>[J. kg(^{-1})]</td>
</tr>
<tr>
<td>h(_v)</td>
<td>specific volume enthalpy h(_v) = h.(\rho)</td>
<td>[J. m(^{-3})]</td>
</tr>
<tr>
<td>k</td>
<td>heat conductivity</td>
<td>[W. m(^{-1}). K(^{-1})]</td>
</tr>
<tr>
<td>t</td>
<td>time</td>
<td>[s]</td>
</tr>
<tr>
<td>w</td>
<td>shift rate of the concasting in the direction of the z-axis</td>
<td>[m. s(^{-1})]</td>
</tr>
<tr>
<td>x,y,z</td>
<td>axes in given directions</td>
<td></td>
</tr>
<tr>
<td>HTC</td>
<td>heat transfer coefficient</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>heat flow in given direction</td>
<td>[W]</td>
</tr>
<tr>
<td>Q(_{SOURCE})</td>
<td>latent heat of the phase or structural change</td>
<td>[W. m(^3)]</td>
</tr>
<tr>
<td>T</td>
<td>temperature</td>
<td>[K]</td>
</tr>
<tr>
<td>V</td>
<td>volume</td>
<td>[m(^3)]</td>
</tr>
<tr>
<td>VX,VY,VZ</td>
<td>unitary heat conductivity</td>
<td>[W. K(^{-1})]</td>
</tr>
<tr>
<td>(\rho)</td>
<td>density</td>
<td>[kg. m(^{-3})]</td>
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References
