Optimisation of a concasting technology via a dynamic solidification model of a slab caster

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Abstract

Solidification and cooling of a continuously cast steel slab and the heating of the mould is a very complicated problem of transient heat and mass transfer. This original three-dimensional (3D) numerical model is capable of simulating the temperature field of a caster. The numerical computation has to take place simultaneously with the data acquisition – not only to confront it with the actual numerical model, but also to make it more accurate throughout the process. The utilisation of the numerical model of solidification and cooling plays an indispensable role in practice. An important step in this analysis is to determine the necessary quantities in the course of concasting. The software enables data acquisition in real time, which is necessary for optimisation. This is ensured by the correct process procedure: real process → input data → numerical analysis → optimisation → correction of process. This procedure is necessary for optimisation (i.e. maximisation of the quality of the process) – especially when reacting to specific needs and conditions in the operation.

Keywords: solidification model, concasting, caster, control.

1 Introduction

The optimisation of production on casters, with the aim of achieving maximum savings and maximum quality of the product is unthinkable without knowledge of the course of solidification and cooling of the concasting.
Solidification and cooling of a concasting, with the simultaneous heating of the mould, is a very complex problem of transient heat and mass transfer. The temperature field in the concasting is determined by using the transient 3D enthalpy balance equation with the Finite Differences Method. It depends on the alloy composition as well as on the cooling rate and shift rate.

The temperature distribution in the concasting is described by the enthalpy balance equation

$$ \rho \frac{\partial H}{\partial t} + \frac{\partial}{\partial x} (\rho v_x H) + \frac{\partial}{\partial y} (\rho v_y H) + \frac{\partial}{\partial z} (\rho v_z H) = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) \quad (1) $$

with the following boundary conditions

1. $T = \text{const.}$
2. $\frac{\partial T}{\partial n} = \text{const.}$
3. $-\lambda \frac{\partial T}{\partial n} = \alpha (T_{\text{surf}} - T_{\text{amb}}) + \sigma \varepsilon (T_{\text{surf}}^4 - T_{\text{amb}}^4)$
4. $-\lambda \frac{\partial T}{\partial n} = \dot{q}$

Considering some physical assumptions and restrictions for the liquid core as well as the mass balance equation, the enthalpy balance equation (1) can be simplified to

$$ \rho \frac{\partial H}{\partial t} + \frac{\partial}{\partial z} (\rho v_z H) = \lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \quad (2) $$

The solution is performed with the boundary conditions:

1. $T = T_{\text{cast}}$ at the meniscus
2. $-\lambda \frac{\partial T}{\partial n} = 0$ at the plane of symmetry
3. $-\lambda \frac{\partial T}{\partial n} = \alpha (T_{\text{surf}} - T_{\text{mould}})$ in the mould
4. $-\lambda \frac{\partial T}{\partial n} = \alpha (T_{\text{surf}} - T_{\text{amb}}) + \sigma \varepsilon (T_{\text{surf}}^4 - T_{\text{amb}}^4)$ in the secondary-cooling area

The heat transfer coefficient $\alpha$ is a function of the local cooling rate and surface temperature, the temperature $T_{\text{amb}}$ is the cooling water temperature in the secondary-cooling zone and the air temperature, where only radiation occurs. Based on the results of previous investigations, the boundary conditions are set identically within each zone individually. This requires a very fine grid, which leads to a large number of equations to solve.

2 Off-line model

The numerical model simulates the forming of the temperature field – not only of the actual concasting of arbitrary shape while it passes through the caster and
even beyond, but also the temperature field of the mould. It is necessary to enhance the model and evaluate it via experimental measurement using a real caster during the process of concasting. This makes it possible to obtain real-time data, which are necessary for the optimisation of the solidification process and their integration into the numerical model. In this way, it is possible to bring the sought after solution as closely as possible to the real conditions of a specific operation. Simultaneously, it ensures the required connectedness within the procedure of: real process → input data → numerical analysis → optimisation → correction of real process. This procedure is necessary in order to be able to react to specific operational conditions (3).

The model analyses the temperature field of the actual concasting while it passes through the primary-, secondary- and tertiary-cooling zone, i.e. through the entire caster, as well as through the most important – or problematic – parts of the caster. Simultaneously, this enables the analysis of the temperature field of the mould and, therefore, the optimisation of its operational parameters, such as cooling, oscillations and the casting flux used. The numerical model fully considers the non-linearity of the task, i.e. the dependence of the thermophysical properties, especially of the concasting material and the mould on the temperature, as it does the dependence of the boundary conditions on temperature and other influences (shift rate, cooling intensity, etc.). The numerical model is equipped with an interactive graphics environment for facilitated entry of the input parameters with the successive automatic generation of the mesh (i.e. pre-processing), as well as modern graphics output that displays the temperature field using contour lines in the various sections, time curves, etc. (i.e. post-processing). The software, based on this model must be user-friendly and it is possible to change the parameters by the trained steelworks staff. In this way it is ready for immediate application in the appropriate offices as an off-line system.

The off-line version of the model of the temperature field is currently in use on the slab casters in three flourishing steelworks in Central Europe. It is fully functional and accurately conducts general analyses of the influences of the various technological measures on the formation of the temperature field of the entire concasting. In a similar way, it helps the staff to analyse the failure state of the caster, which is signaled by a break-out prevention system. Furthermore, it enables the user to design even a non-traditional file or combination of technological interventions for the optimal formation of the temperature field with the aim of enhancing the quality of the concasting while maintaining or even raising the volume of production. The results of this analysis and the corresponding optimisation measures are confronted with experimental results and the achieved quality of the semi-finished product. A comparison of several designed variants of technological measures could provide solutions to possible problems. A disadvantage of the off-line system is mainly a considerable delay – from the occurrence of the failure to the identification of the cause and the corrective action – and the tedious process of obtaining input data for computation.
3 On-line model

One dynamic 3D on-line model of the temperature field of slabs is undergoing a non-stop trial run in one operation because steel slabs are produced 24 hours per day. The off-line version will be utilised further – for various analyses within the caster operation, independently of the real melting process, product range, cooling intensity, shift rate, etc.

The on-line model enables a multiple increase in the speed with which the temperature field of the concasting is computed – both with the application of more sophisticated software as well as hardware. As a result of this, it will be possible to monitor the formation of the temperature field – in real time – within the mould, the secondary- and maybe even the tertiary-cooling zones, and also to utilise this information for the optimisation of the control of the caster as a whole as well as its individual parts. Furthermore, it can be used in the re-design (modernisation) of the actual caster or the range of its products.

The model adjusts the casting parameters (especially the shift rate, the oscillations of the mould, the cooling of the mould, the cooling intensity of the cooling jets) according to the real time data acquired and the calculated values. Furthermore, the system enables the archiving of the calculations of the real melts (depending on the size of the data storage) and their potential traceability. With melts where there are defects, it will be possible to re-play their history, simulate them again with the off-line system and to propose certain technological

Figure 1: The main screen of the dynamic solidification model.
measures (e.g. a change in the shift rate or the spraying plan) in order for these defects not to recur in the future melts.

Another capability of the on-line system is the raised quality and the accuracy of the input data, their mutual connections and qualitative parameters, including the setting of the limit values. This creates a system, which, not only quickly but also very accurately, displays the actual temperature field of the concasting during the process, including all necessary technological data concerning the caster.

The basic condition for the successful running of the system is the suitable hardware and its optimal connection to the existing information system of the caster as well as the connection to the lowest control level of the caster. The functioning of the on-line model of the temperature field is conditioned by the availability of the following on-line input data, as is in the case of slab casting: the pouring temperature, the dimensions of the concasting, the chemical composition of the poured steel, the shift rate, the position of the level within the mould, the temperatures within the walls of the mould, the oscillations of the mould, the difference in the cooling water in each mould plate, the flow of water through each mould plate, the settings of the flow of water and the pressure of the air through the secondary-cooling zone, the temperature from the pyrometers within the secondary-cooling zone.

This data is passed on to the temperature field model through a newly developed interface programme designed in accordance with industrial standards such as SQL and OPC. It is not suitable for the temperature model to read the data from the technology directly, because the technology is heterogeneous and

Figure 2: An example of a melt at the beginning and end of the casting.
there are possible changes that would always require a change in the software of the temperature model. The interface programme is based on object-oriented technology, which enables, through various models, to solve the connections to various technologies and, simultaneously, communicates with the temperature model via standard objects.

The data are obtained at various time intervals, however, in order for this data – these values – to be processable further, it is necessary for the communication programme to be able to:

1. Eliminate all irregular values using filters for all quantities, which would find out whether the value of the quantity is valid, i.e. whether it lies within the given interval.

2. Interpolate these points and establish continuous functions for each quantity.

3. Establish a common time base.

4. Read the interpolated value of the function of each relevant quantity within each (equal) time step.

The basic evaluated parameters are: the courses of the surface temperatures along the length of the caster, the thickness of the shell while it passes through the caster, the length and shape of the liquid centre of the concasting, the course of the iso-solidus and iso-liquidus lines along the caster (Fig. 1), the distributions of temperatures – the temperature field – in an arbitrary cross-section and moment in time.

The on-line model will automatically set the technological parameters of the casting process in order to achieve the required quality of the cast steel.

![Figure 3: The drop in the shift rate and the reaction of the model.](image-url)
4 Results

Fig. 2 illustrates the shift rate history, the calculated metallurgical length and the temperatures measured using the pyrometers for the relevant melt. It is obvious from the picture that the reaction to the drop in the shift rate really reduced the metallurgical length. The graph also confirms the fact that the change in the shift rate affects the quality of the surface, which can be seen in the increased oscillations of the measured surface temperatures (2). Fig. 3 illustrates the shift rate history of another melt – in the occasion the tundish was changed (without interrupting the casting process) and also after finishing the casting. The graph also indicates the variation of the (calculated) metallurgical length, which is confirmed by trend of the measured temperatures.

5 Conclusion and outlook

Comparisons between measured and predicted surface temperatures show that the predictions are, on average, within ±25 °C of the measured values.

The presented model is a valuable computational tool and accurate simulator for investigating transient phenomena in slab-caster operations, and for developing control methods, the choice of an optimum cooling strategy to meet all quality requirements, and an assessment of the heat-energy content required for direct rolling. It should bring about quality improvement in the case of non-stable casting conditions. The on-line version will automatically set the technological parameters of the casting process in order to achieve the required quality of the cast steel.

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Nomenclature

\begin{align*}
T & \quad \text{temperature} \quad [\text{K}] \\
H & \quad \text{specific enthalpy} \quad [\text{J/kg}] \\
\rho & \quad \text{density} \quad [\text{kg/m}^3] \\
\lambda & \quad \text{heat conductivity} \quad [\text{W/m.K}] \\
v_z & \quad \text{shift rate} \quad [\text{m/s}] \\
\alpha & \quad \text{heat transfer coefficient} \quad [\text{W/m}^2\text{K}] \\
T_{\text{surf}} & \quad \text{surface temperature} \quad [\text{K}] \\
T_{\text{amb}} & \quad \text{ambient temperature} \quad [\text{K}] \\
T_{\text{cast}} & \quad \text{casting temperature} \quad [\text{K}] 
\end{align*}
\[ \sigma \quad \text{Stefan-Boltzmann constant} \ (= 5.76 \times 10^{-6} \text{ W/m}^2\text{K}^4) \]
\[ \varepsilon \quad \text{emmisivity} \ (= 0.8) \]
\[ q \quad \text{heat flux density} \quad [\text{W/m}^2] \]

References

