

# DEVELOPMENT, IMPLEMENTATION AND VERIFICATION OF A TRANSIENT NUMERIC SOLIDIFICATION MODEL OF A CONTINUOUS BLOOM CASTER AT VOESTALPINE STAHL DONAWITZ

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## Abstract

voestalpine Stahl Donawitz is operating a 3-strand 390x283 mm<sup>2</sup> bloom casting machine, mainly for the production of rails. During a 3-year collaboration with the former Christian Doppler Laboratory for Metallurgical Fundamentals of Continuous Casting Processes at the University of Leoben, a transient two-dimensional numeric solidification model has been developed, implemented and verified. The present paper comprehensively describes the three key-aspects of this complex development: Firstly, the formulation of appropriate numeric algorithms for computing the solidification in a transient two-dimensional model is outlined. The used algorithm yields a thermal solution and the solidification conditions within a few minutes. Secondly, the identification of correct and appropriate thermal boundary conditions over the whole casting length requires detailed and intensive measuring via plant trials. One example, the thorough identification of the heat withdrawal in the selected caster's mould, is explained in detail – together with the subsequently necessary inverse numeric modelling. Additionally, the applied techniques in order to establish the cooling conditions in the secondary cooling zone are presented. Thirdly, the assessment of the model's quality is obtained by specific, especially targeted measurements at the caster – their description and some typical results of the model and their significance conclude the paper. In future, the developed model will not only serve as a basis for process optimisation but also for the implementation of further metallurgical models such as microstructure evolution or defect formation models.

## Keywords

Continuous casting; numeric modelling; heat transfer; mould instrumentation; plant trials;

## Introduction

voestalpine Stahl Donawitz GmbH & Co KG is part of the Division Railway Systems of voestalpine AG. It supplies the Railway Systems rolling mills with high quality billets and blooms for the production of railways, wires and seamless tubes. In addition – as shown in Figure 1 – external customers besides voestalpine AG are also supplied with semi finished-products.

The focus of the present paper is modelling the solidification in the three strand bloom caster CC2,

which was commissioned in 1980 and revamped in 1998 and 2004. The main machine data are listed in Table 1. The production spectrum of voestalpine Stahl Donawitz GmbH & Co KG covers a wide range of different steel grades, starting from low carbon steels for drawing grades up to high carbon steels for roller bearing steel. The present machine is mainly used for the production of high quality rail steel blooms which are directly delivered to the adjacent rolling mill of voestalpine Schienen GmbH.

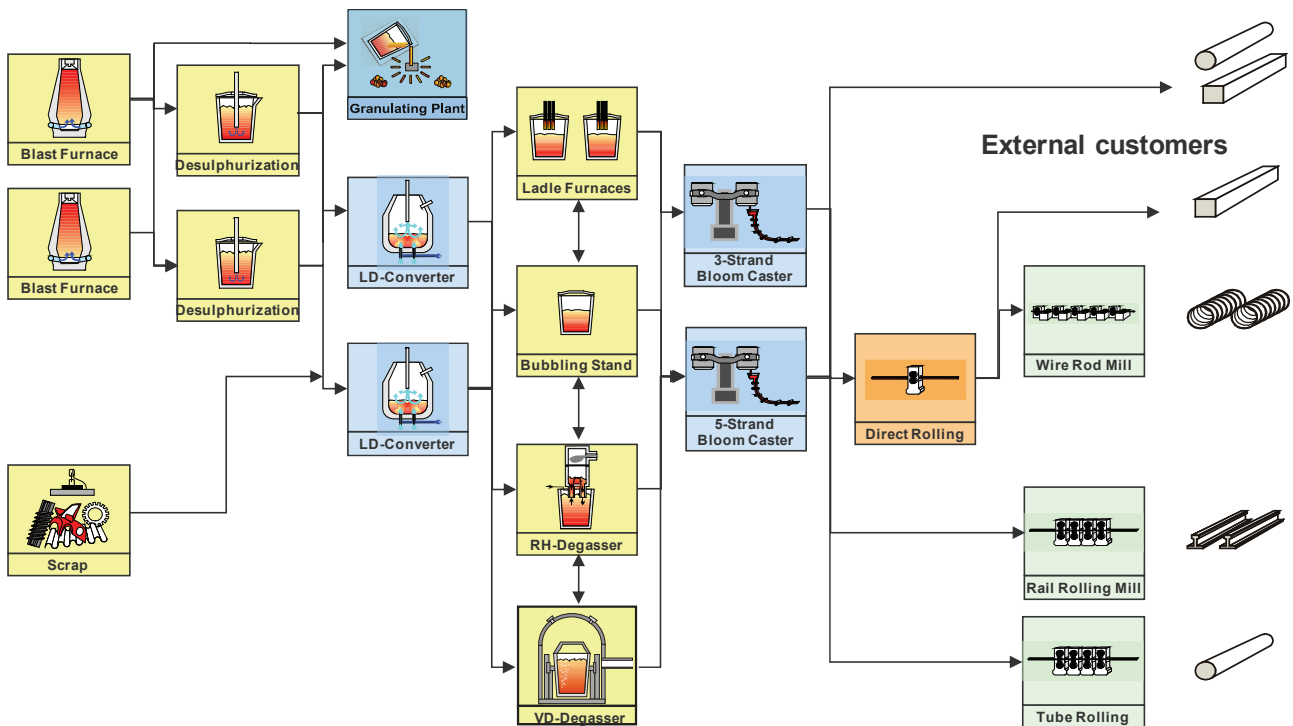


Figure 1: Flowchart of voestalpine Stahl Donawitz GmbH & Co KG; total production on the casters is 1.55 Mta<sup>-1</sup>.

#### Main Machine Data

Start Up Year	1980
Revamping	1998, 2004
Capacity	0.8 Mta <sup>-1</sup>
Heat Size	67 t
Number of strands	3
Radius	9 m
Metallurgical length (max)	24.0 m
Mould length	0.8 m
Mould type	Plate, straight (283x390mm <sup>2</sup> )
Bloom section	283x390 mm <sup>2</sup> 230 mm round (optional)
Casting Speed	0.5 – 0.75 mmin <sup>-1</sup> (283x390mm <sup>2</sup> )
Tundish capacity	13 t
EMS	Mould stirrer
Secondary cooling	6 zone spray cooling

Table 1: Main data of CC2 bloom caster.

In order to provide the basis for a further optimisation of the casting process, a two-dimensional transient solidification model has been developed. Owing to the wide range of produced products, the following preconditions were set to the model:

- Incorporation of the influences of different material properties such as specific heat capacity, thermal conductivity and solidification range;

- Differentiation of the changes in heat withdrawal in the mould owing to varying steel grades and casting speeds;
- Implementation of the effects of water spray cooling according to the water distribution of the different cooling programmes.

Furthermore, the computation of temperature distribution and solidification progress in two dimensions was to be achieved with the best compromise between computational efficiency and calculation accuracy.

In the following, the necessary steps for developing such a model will be outlined: Firstly, a possible algorithm and method for computing the transient two-dimensional solidification will be explained. Secondly, the paper will focus on the determination of thermal boundary conditions in the mould as well as in the secondary cooling zone. In order to gain a thorough view on local differences in heat withdrawal in the mould, the local heat transfer was determined by measurements with an instrumented mould in

## Algorithm Formulation

Generally, the algorithmic basis for a solidification model is the solution of the law of energy conservation. Inserting FOURIER's law as a constitutive equation for energy yields the following parabolic differential equation,

$$\frac{\partial}{\partial t}(\rho H(\vartheta)) = \nabla \cdot (\kappa(\vartheta) \mathbf{grad} \vartheta), \quad (1)$$

where  $t, \rho, H, \vartheta, \kappa$  are time, density, enthalpy, temperature and thermal conductivity, respectively. The left hand side accounts for transient effects while the right hand side accounts for heat conduction in  $n$  directions; convection effects are neglected. The transient term, which requires a relationship between enthalpy and temperature and possibly a consideration of latent heat of fusion is highly important in the present work.

With the exception of beam blank casting, simulations of continuously cast products are relatively simple regarding their computational domain, meaning that no complex geometrical conditions need to be considered. Thus, the scope of

## Identification of Boundary Conditions

As the quality of a solidification model highly depends on the quality of the applied boundary conditions (BC), a reliable solidification model will involve obtaining ascertained and verified thermal BC for the caster. In addition, the exact thermal conditions are always unique for every caster due to the multiple specifics of each machine. Furthermore, from a metallurgical viewpoint, the thermal BC will often differ with the cast steel grade – due to the changing behaviour of different steels, casting and cooling conditions are often changed.

## Mould Heat Transfer

The heat removal in the continuous casting mould is a decisive factor for product quality and process safety. This quantity is affected by different process parameters, most noticeably by the steel composition, the casting velocity, the mould powder and the mould taper. Although the total heat transfer

order to record the temperature profiles during casting. Thereafter, an inverse model was used to compute the heat withdrawal in the mould. With regard to the secondary cooling zone, the heat transfer is calculated on the basis of the local water distribution of the spraying nozzles. Thirdly, the verification of the model results via plant measurements of surface temperature or solidification progress will be explained.

possible numerical methods is not only limited to those of the finite element methods – the use of finite differences/volumes methods is likewise also a possible choice. A comprehensive description of the basics of these numeric methods can be found in the literature<sup>[1]</sup>.

Seeing that computational effort is a substantial criterion in the present study, a careful choice of the numerical methods has to be done. In this context, a previous study<sup>[2]</sup> has shown that the alternating-direction implicit method offers an attractive compromise between computational efficiency and result accuracy. Originally this method was not apt for solidification problems, however the modified alternating-direction implicit (MADI) method<sup>[2]</sup>, which contains necessary modifications for the consideration of the release of latent heat during solidification and the effects of changing material properties (with temperature), is an interesting method which was also used in the present work. Details to the mathematical basis and the algorithm development can be found in [2].

between strand and mould is easily calculated from the temperature increase between primary water inlet and outlet, it only allows general conclusions on the conditions inside the mould. However, local changes in the heat transfer affect the uniformity of shell growth and in consequence the probability of surface and subsurface defect formation. Although the determination of the local heat transfer is rather complex, demanding the instrumentation of a mould with numerous thermocouples and subsequent inverse modelling, this method was chosen for the present work in order to compile a sophisticated solidification model. Moreover, with regard to the cast geometry, the temperature and shell thickness of the corners of the strand is of high interest – an exact computation is only possible if locally varying boundary conditions are applied.

In the present work the plate mould was instrumented with a total of 46 type-K thermocouples in eight

different planes of the mould. In order not to disturb the water flow, the thermocouples were inserted through the support bolts of the backup plate of the mould into the copper plate at a distance of 4 mm from the mould hot face. In order to ensure the contact between the thermocouple and the copper, a constant force was applied from the back end of the thermocouple by a spring and a screw fitting. Moreover, sealings were inserted at all necessary interfaces.

Assuming a high degree of similarity between the two narrow and the two broad faces of the mould, one

narrow and one broad face were instrumented completely along the centre axis. Additionally, the near-corner area was instrumented for two facing edges. The second faces were only instrumented partially for a local verification of the measured temperatures at different positions. Figure 2 shows a photograph of the instrumented mould before its deployment; Figure 3 shows the instrumentation concept on narrow face 1 and broad face 1. The temperatures were recorded at a frequency of 20 Hz. Hence, the recorded values were time-averaged with a data acquisition unit linked to a commercial PC.

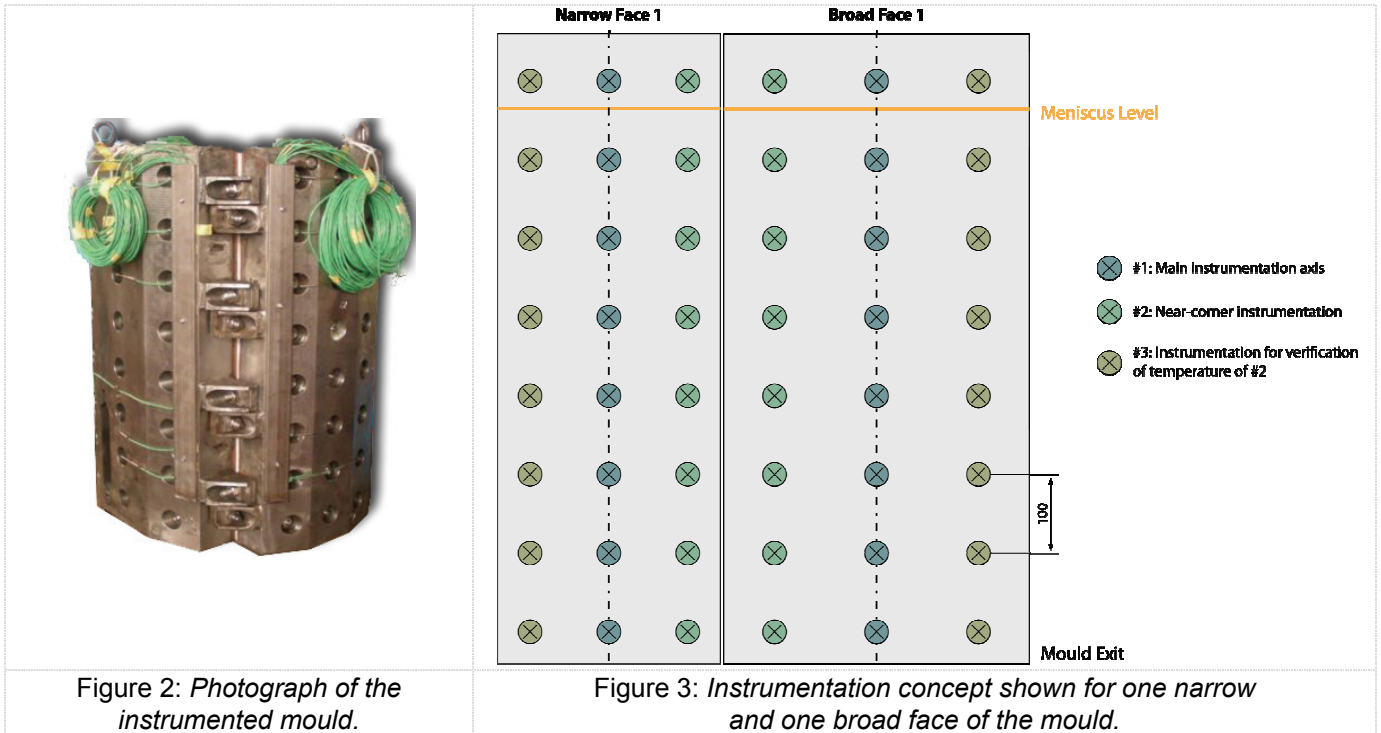


Figure 2: Photograph of the instrumented mould.

Figure 3: Instrumentation concept shown for one narrow and one broad face of the mould.

The measurements conducted for the present work encompass a total measuring time of app. 50 production days for a wide variety of steel compositions and casting parameters. Since a detailed description and comparison of the influences

of steel compositions and casting parameters would go beyond the scope of this publication, only one specific parameter set, shown in Table 2, has been selected for all following discussions.

wt.-%C	wt.-%Si	wt.-%Mn	wt.-%Ni	wt.-%Cr	$v_c, \text{mmin}^{-1}$
0.75	0.30	1.0	0.025	0.035	0.60

Table 2: Composition of investigated steel grade A.

Figure 4 shows the typical thermocouple response along the main instrumentation axis of the broad face for a measurement time of app. 40 min. It can be seen that a very stable response was recorded – a general observations for the whole measurement campaign. When compared to previous studies [e.g. 3], this results indicates that the used measuring setup is very suitable for such measurements.

The recorded temperatures were hence averaged for a period of one complete heat, yielding a temperature distribution as it is indicated in Figure 5. The com-

parison between narrow and broad face shows two observations: Firstly, owing to the influence of the steel stream from the submerged entry nozzle, the temperature decrease after the meniscus region is not as pronounced as it is for the broad face; secondly a better contact between mould and strand observed in the lower part of the mould. Next to the shown temperature distributions along the centre axes, naturally also the temperature distributions along the near-corner areas were employed for all further investigations.

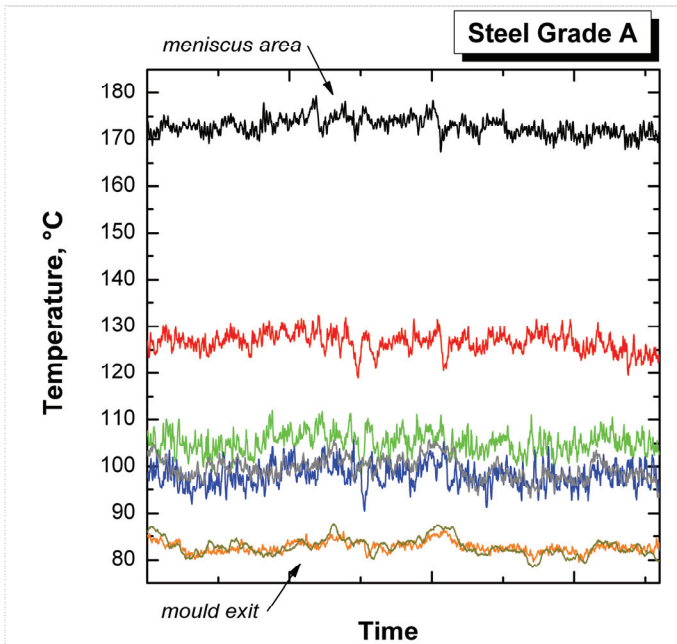


Figure 4: Typical thermocouple response at the centre axis of the broad face for a measuring period of 40 min.

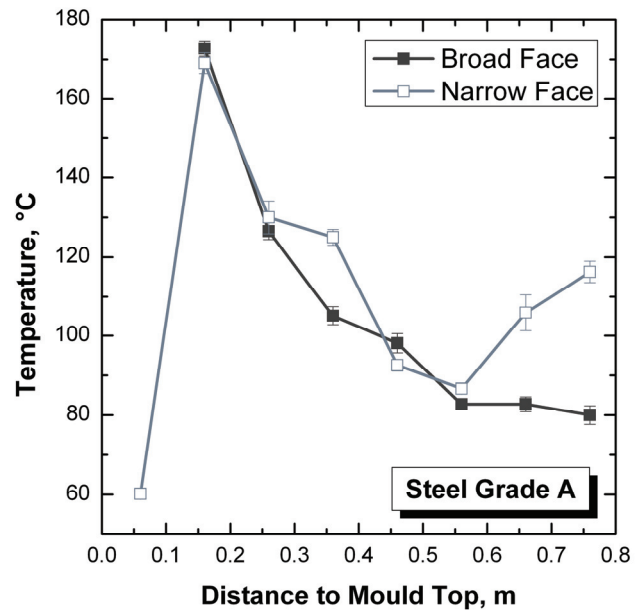


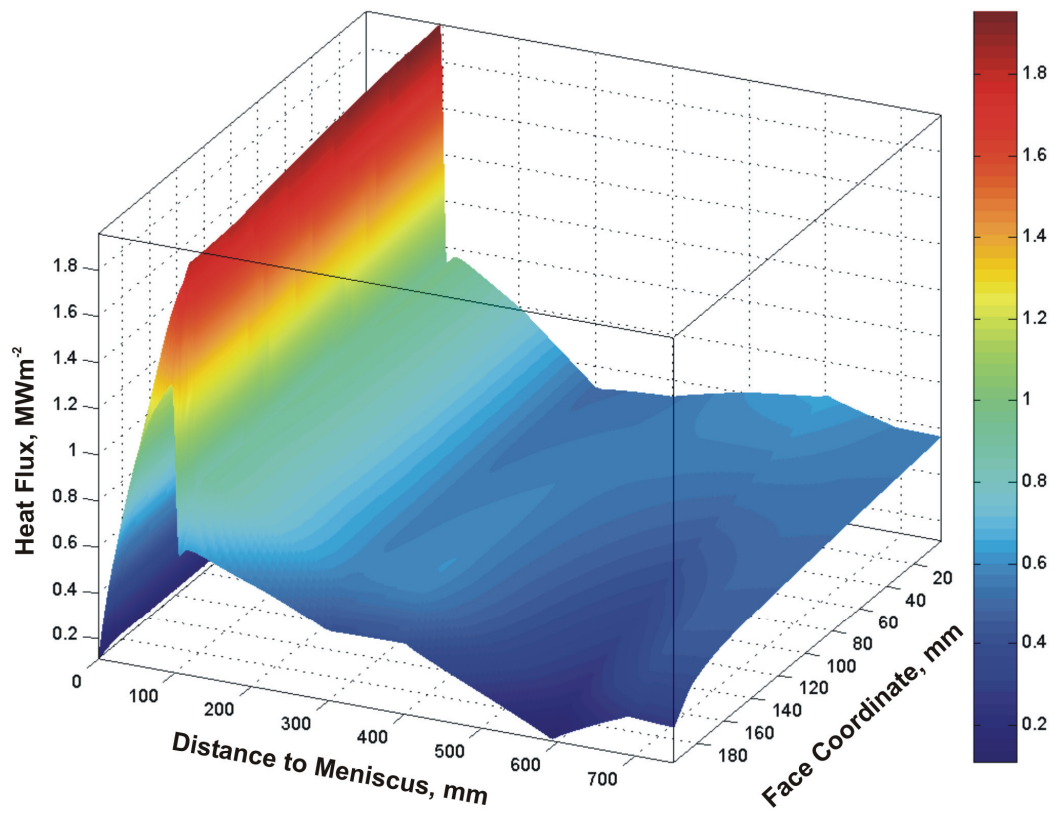
Figure 5: Time-averaged thermocouple response for one complete heat along the centre axes of broad and narrow face.

In order to determine the local heat flux on the basis of the conducted temperature measurements, use was made of inverse modelling. The idea behind this concept is – opposed to that of conventional numeric modelling where a desired quantity is computed from a given set of boundary conditions – to establish one or more boundary conditions by targeted iterations to a series of already known resulting values. Details to this technique and the employed algorithms can be found in the literature<sup>[1,3]</sup>. For the present problem the time-averaged thermocouple responses of the positions indicated in Figure 3 were taken as an input parameter for a transient two-dimensional inverse model; the temperature-dependent material properties were calculated with the commercial software program IDS16<sup>[4]</sup>. Thus, a three-dimensional image of the heat withdrawal could be gathered for all steel grades and casting parameters. Examples of the results of the inverse model can be seen in Figure 6.

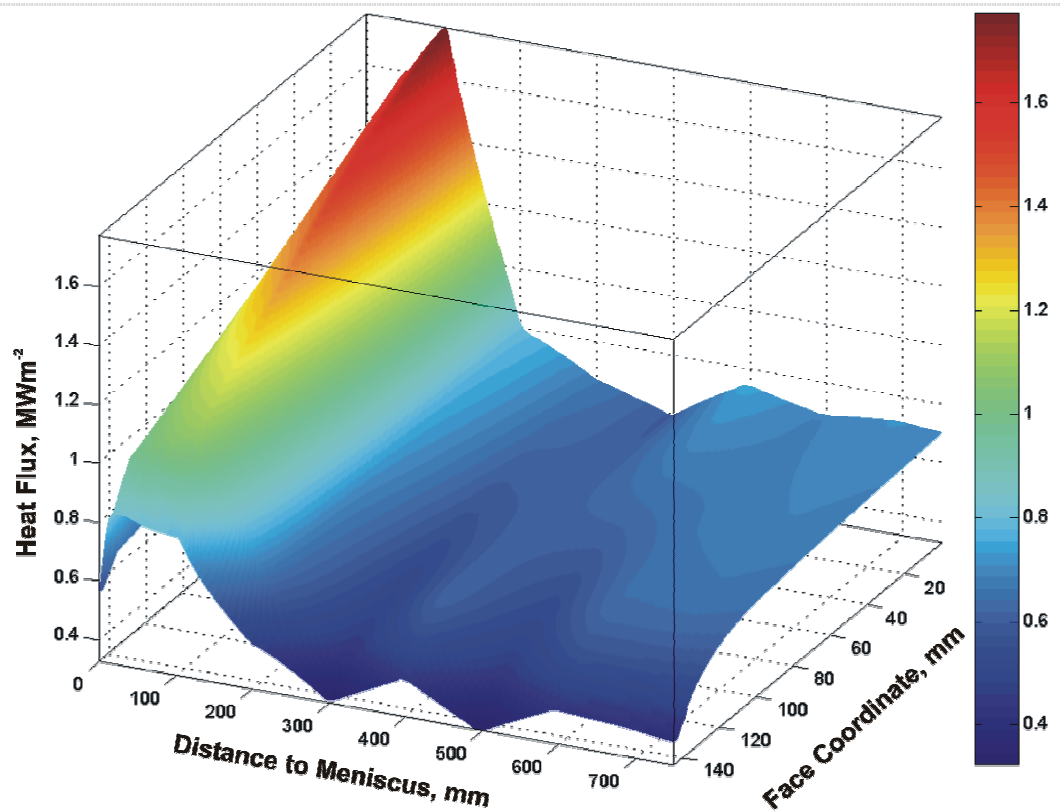
The visualisation in Figure 6 shows several interesting results: Firstly, the expected behaviour that the heat flux decreases towards the mould edge owing to an increasingly two-dimensional heat

transfer in the corners (leading to a more pronounced contraction of the shell). Secondly, with regard to the absolute peak of the heat flux, a higher withdrawal is observed on the broad face of the mould. It is evident that such a comprehensive consideration of the heat withdrawal will substantially improve the quality of the solidification model as a whole since fluctuations and differences on a local scale will also influence the surface temperature at the mould exit over the bloom cross section.

In order to assess the overall quality of the inverse model, the integral heat flux – which can on the one hand be determined by integrating the heat flux distribution in Figure 6 and, on the other hand, be measured on the plant via the difference of cooling water temperature between mould inlet and outlet – was taken as a reference quantity. Figure 7 shows a comparison of measured and computed integral heat fluxes for different references states. As can be seen, the consistency of the results is very satisfactory which hence increases the reliability of the overall solidification model.



a)



b)

Figure 6: Calculated heat flux distribution on a) the broad face and b) the narrow face for steel grade A. Face coordinate 0 corresponds to the centre axis of the mould; the maximum value to the edge of the mould.



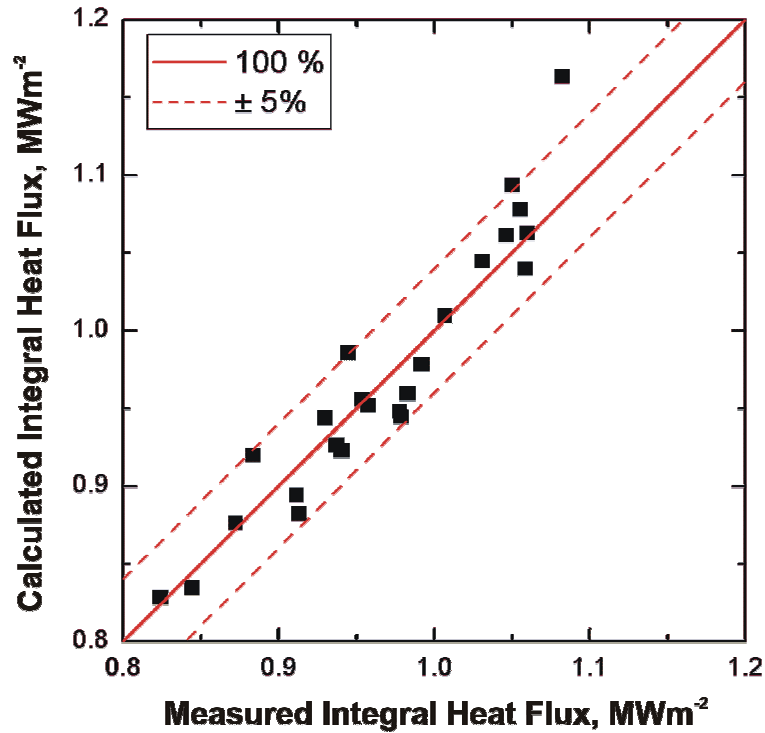


Figure 7: Comparison of measured and calculated integral heat fluxes. Each measurement point indicates a different casting condition or steel grade.

## Boundary Conditions in the Secondary Cooling Zone

For the present solidification model, the thermal boundary conditions in the secondary cooling zone and the bending and straightening area are composed of two factors: a convective heat transfer by the spray cooling and radiative heat dissipation from the radiating strand surface. The physics behind the latter is quite straightforward,

$$h_{rad} = \sigma \varepsilon (T_s^2 + T_{ext}^2) (T_s + T_{ext}), \quad (2)$$

where  $h_{rad}$ ,  $T_s$ ,  $T_{ext}$ ,  $\sigma$  are the radiative heat transfer coefficient, the surface temperature, the external temperature and the Stefan-Boltzmann constant, respectively. The emissivity  $\varepsilon$  is usually a function of the amount of strand scale formation, which strongly depends on the carbon content.

## Model Results and Verification

The combination of the above described techniques yields a fully transient two-dimensional solidification model; its results are mainly the surface temperature and the fraction of solid as a function of strand position. Additionally, derived quantities such as temperatures at any point in the strand, temperature gradients, or solidification velocities can be deduced.

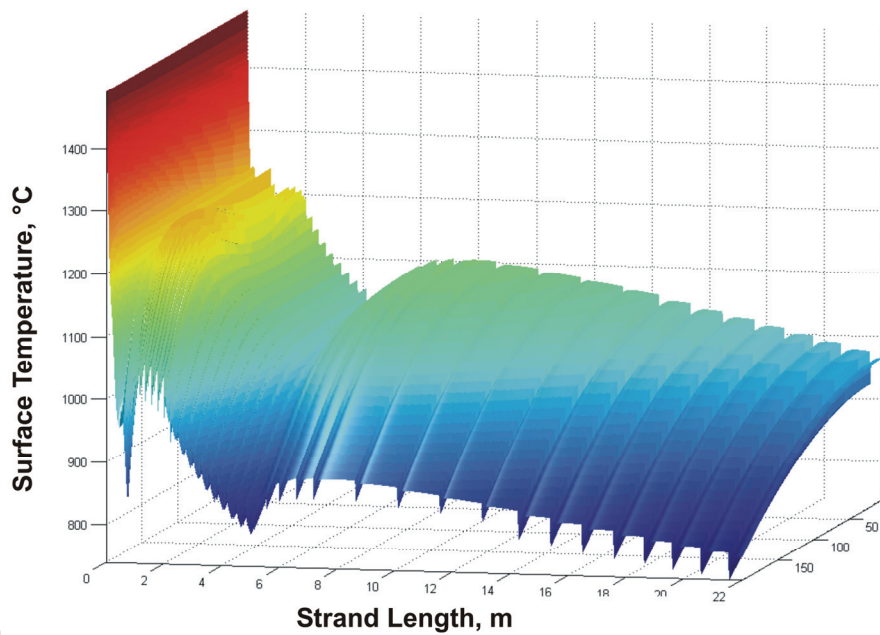
With regard to the convective term of the water spray cooling, the heat withdrawal can be correlated with the water impact amount at the strand surface. Wendelstorf et al.<sup>[5]</sup> have built an experimental setup to determine the heat transfer coefficient of spray nozzles directly as a function of nozzle geometry, water flow rate and surface temperature. The dependency found by the authors was also used for the present work. However, the water distribution was assumed to be distributed by a Gaussian-curve over the sprayed area. This assumption is consistent with practical observations and also with measurements carried out with different spraying nozzles<sup>[e.g. 6]</sup>. The width of the Gaussian curve was determined by practical observations of the spraying cone.

In order improve the knowledge and the possibilities of determining heat transfer coefficients of spraying nozzles, a novel measuring stand for spraying nozzles employed in continuous casting is presently being taken into operation at the Chair of Metallurgy.

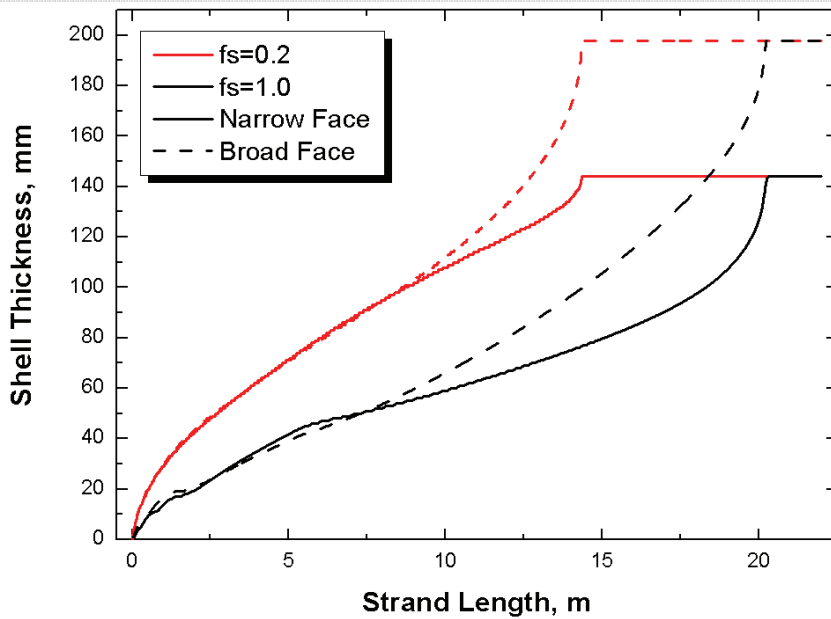
Such parameters can then be input values for a further application of microstructure, precipitation or segregation models. In order to exemplify the potential of the present model, Figure 8a shows the surface temperature evolution of the broad face along the complete strand distance; the effects of spraying nozzles and roll contact are fully visible. Figure 8b

shows the shell growth at different fractions of solid along the centre axes of broad and narrow face. The results clearly reflect the influences of the complex boundary conditions in the primary and secondary cooling zone, as well as the cooling of the strand

after the secondary cooling zone. It should be mentioned that these results show only a fraction of the capabilities of the model – in total, 12 different steel grades are currently implemented with the possibility of computing any feasible casting state.



a)



b)

Figure 8: Typical results of a transient two-dimensional solidification model: a) surface temperature evolution along the strand length for the broad face and b) shell thickness for different fractions of solid for broad and narrow face.



Lastly, in order to verify the quality of the presented model, several plants trials were carried out:

Firstly, a scanning optical pyrometer was installed at app. 9 m distance from the meniscus in order to measure the surface temperature of the strand surface. The pyrometer was installed on a swivelling device which allowed recording the temperature over a whole cross section of the strand – from the centre axis of the broad face over the corner to the centre axis of the narrow face. For all measurements an emissivity coefficient of 0.84 was used. Thus, an excellent reproduction of the temperature distribution over the strand surface, including corner temperatures could be gained. Owing to the unfriendly measuring environment, it was not possible to generate a data basis as big as for the instrumented mould, nonetheless in total 15 different casting states, with a reproduction factor of 2–3 could be recorded. Hence, these casting states were compared to the results of the solidification model. Figure 9 shows such a comparison for the surface temperature of the narrow side. Under consideration of a certain degree of irregular scale formation, the consistency of the solidification model with the practical measurements is very satisfying. The deviation of surface temperatures in the region of the centre axis can be explained by the fact that the

angle at which the pyrometer was pointing at the strand surface was not optimal as the swivelling pod of the pyrometer was installed at a certain distance from the corner of the strand. This implies that for positions far away from the corner, the pyrometer was not measuring at a 90° angle from the surface, which leads to a certain systematic measurement error.

Secondly, in order to also verify the correct computation of the solidification conditions inside the strand, the shell thickness was measured at a certain position in the strand. By the application of overcritical stresses on the strand during solidification, hot tears were purposefully generated in the fragile shell. The stresses were applied by rolling small wedges into the strand in the secondary cooling zone. It is well known that owing to the low ductility of the solidification region, such stresses lead to the formation of hot tears. In order to detect the position of the tears (and thereby determine the shell thickness), slices were cut from the cast blooms and evaluated metallographically. Thus, it was possible to determine the shell thickness for different casting velocities – a quantity which is an excellent basis for the verification of the results of a solidification model. Figure 10 shows the comparison of these results and underlines the reliability of the present model.

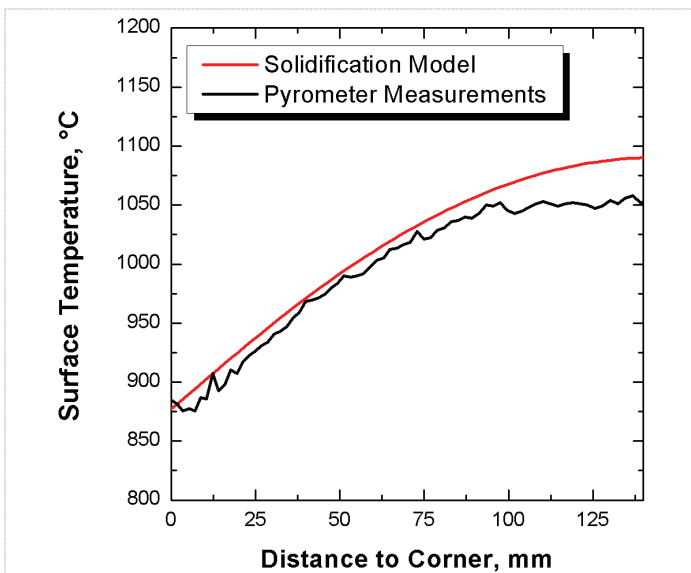


Figure 9: Comparison of calculated temperature profile along the narrow side of the bloom and measured temperatures.

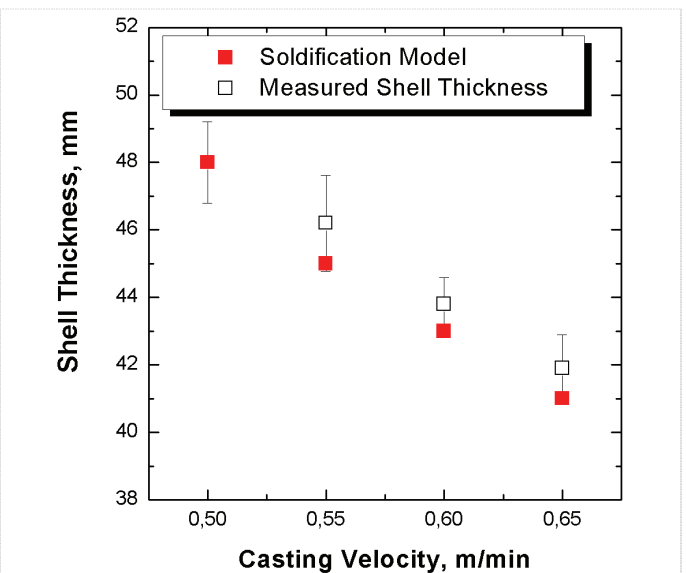


Figure 10: Comparison of calculated and measured shell thicknesses for different casting speeds.

## Summary and Conclusion

The present paper described the comprehensive development of a solidification model for the bloom caster CC2 at voestalpine Stahl Donawitz & Co KG in a collaboration with the Chair of Metallurgy at the University of Leoben. Firstly, the necessary algorithmic basics for the computation of solidification were presented and a possibly algorithm which yields the results in a reasonable computation time was mentioned. Secondly, the focus of the paper was the determination of correct and verified thermal boundary conditions in the mould as well as in the secondary cooling zone. It was explained that

complex measuring and modelling work is necessary in order to create a thorough picture of the influences of different cast steel grades and casting conditions. Lastly, the results capabilities of such a solidification model were presented; with the aid of targeted plant measurements also the reliability of the model results could be verified and assured.

In future, the developed model will not only serve as a basis for process optimisation but also for the implementation of further metallurgical models such as microstructure evolution or defect formation models.

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