# NEW APPROACHES IN MOULD SLAG FILM PREDICTION AND VISUALIZATION [1]

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**Abstract**
Editing process data of different continuous casting machines into a mathematical-physical mould model reveals new insights into the conditions in the mould during continuous casting of steel. The mould details as well as the operational steel and flux conditions are brought into focus. The aforementioned parameters are decisive factors for the progression of heat transfer resistance within the slag film as a function of its position in the mould and the respective casting speed. Directly related to this is the slag film thickness between the strand shell and the copper plate. The model presented facilitates adjustment of the casting flux to the individual requirements of different continuous casting plants. Thus, improved quality and operating safety will be accomplished.
**Keywords**: Mould slag film; Mould flux; Heat removal; Mouldscreen®.

## NOVO MÉTODO DE PREDIÇÃO E VISUALIZAÇÃO O FILME DE ESCÓRIA

**Resumo**
A análise de dados de processo de diferentes máquinas de lingotamento contínuo através de um modelo matemático-físico do molde de lingotamento revela novos mecanismos com relação às condições existentes na interface metal-escória do molde durante o lingotamento contínuo de aço. As características de projeto do molde de lingotamento bem como as condições operacionais relativas ao aço e filme de escória formado são analisadas detalhadamente. As condições acima mencionadas são fatores decisivos para determinação da transferência de calor através do filme de escória em função da sua posição ao longo do comprimento do molde e da respectiva velocidade de lingotamento. Neste sentido, podemos destacar a influência da espessura do filme de escória formada entre a pele em solidificação e a parede de cobre do molde de lingotamento nas taxas de extração de calor. O modelo matemático desenvolvido possibilita o ajuste das propriedades físicas do pó fluxante aos requisitos de qualidade exigidos por diferentes plantas de lingotamento contínuo, e permite alcançar melhoria de qualidade e maior segurança operacional.
**Palavras-chave**: Filme de escória do molde; Fluxo de molde; Extração de calor; Mouldscreen®.

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## Basic Principles

Up to date the slag film thickness between strand and mould plate could only be predicted rudimentary, considering real operation parameters of continuous casting machines. Model calculations describing a slag film, consisting of not yet measurable liquid and re-solidified casting powder layers, need to reflect the entire casting mould. Particular attention must be given to the heat transfer within the mould slag film. Generally, such models are based on physical equations. Starting from there, the simplest solution leads towards numerical analysis or statistics including the disadvantages of very complex programming, overlong computing times for practical usage, and quite often results deviate from reality.

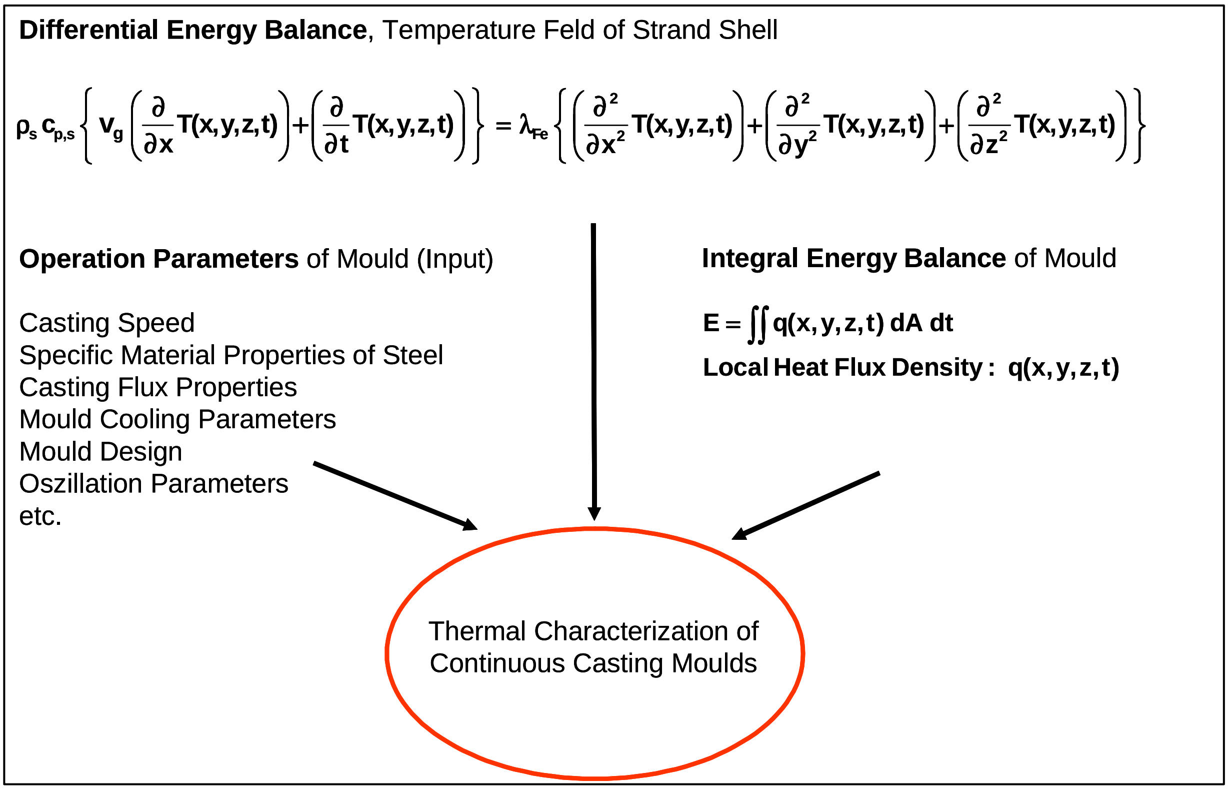


**Figure 1:** Basic principles and model components.

Analytic solutions of the fundamental physical equations and the resulting analytical models are rather rare when it comes to continuous casting. The mathematic-physical descriptions of the thermal events inside continuous casting moulds explained in this work, present an ambitious link between differential and integral formulations of the energy theorem using real operation parameters of continuous casting machines.

Details on the formulas given in Figure 1 shall not be discussed at this point, therefore it is suggested to refer to literature.[1,2]

The model delivers all relevant parameters, such as:

- strand shell thickness,
- local and integral heat flux density,
- water temperature inside the cooling channels/slots,
- copper plate temperatures on hot and cold sides,
- temperature field inside the strand shell

- heat transfer resistance and thickness of the slag film between strand and mould

Moreover, the model already has been applied successfully at continuous casting moulds for slabs, thin slabs and round billets.
So far, parameter studies comprising thousands of operation conditions based on numerical models only, were very hard to execute.
Applying the mould model, this now becomes very easy.
The model permits diverse analyses of process conditions, comparative studies between operation procedures and construction parameters of various continuous casting moulds. Improvements and process optimisations could be worked on.
S&B Industrial Minerals GmbH, Stollberg Division, focuses on the optimal adjustment of casting parameters for the infiltration of liquid slag from casting flux at the meniscus, good lubrication, heat transfer control in the mould adjusted to the operation conditions, protection against oxidation, as well as process reliability and product quality. Several investigations show that the model is capable of predicting the break-out risk according to the operating status (4).
Apparently a correlation exists between the smallest break-out ratio and a certain value of heat transfer resistance within the slag film at the meniscus area. It is plain to see that this factor not only depends on the liquid slag characteristics but also on the construction and operation of the mould, e.g. its cooling and oscillation.

## MOULDSCREEN®

In order to visualize the model results STOLLBERG developed the software tool MOULDSCREEN®. It sources information from a STOLLBERG casting powder data base and connects the customer-specific plant parameters with results of the mathematic-physical analyses. Data transfer can be arranged via screens or online (future) (Figure 2).

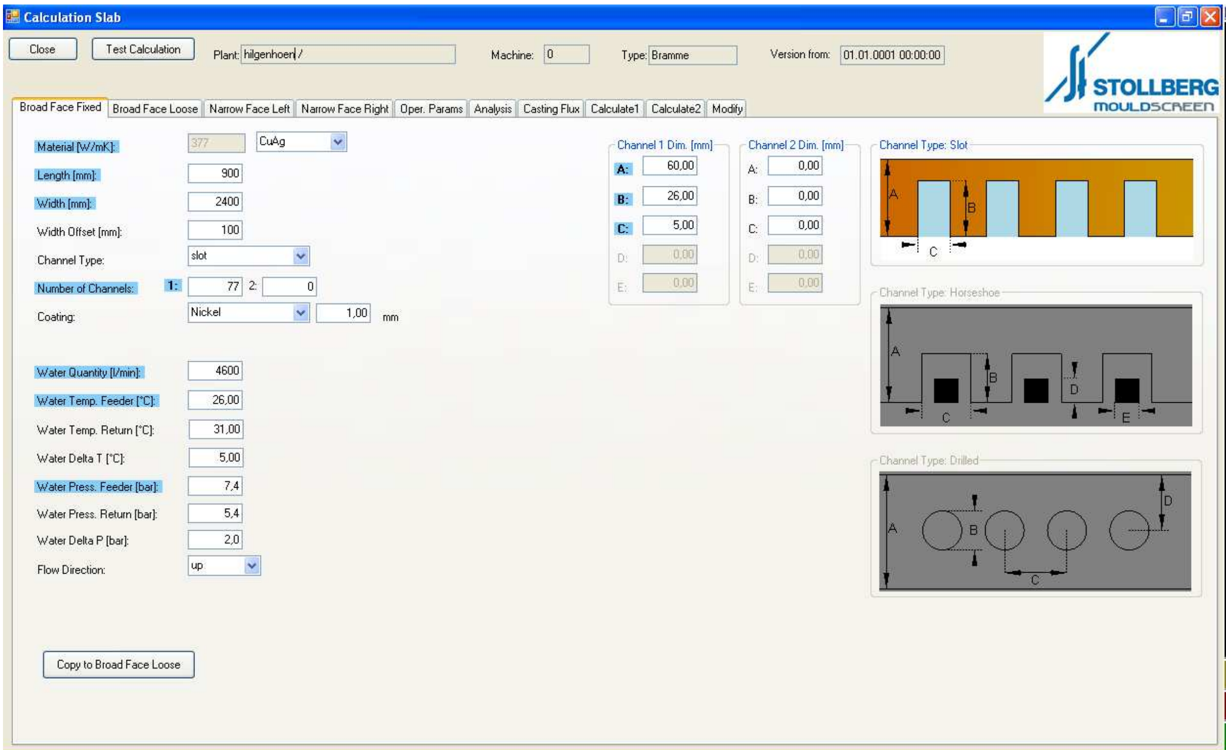


**Figure 2:** Input of mould geometry and operation data.

For slab and thin slab moulds the operation data of both narrow and broad faces are edited and evaluated separately. For round formats, a special calculating module for this type is loaded. Algorithms for any other formats, such as blooms, billets and beam blanks, are scheduled. Thermo-couple readings, if available, will be considered too in the future.

After input of the steel analyses and casting powder type various screens visualize the model calculation results graphically. Figures 3 and 4 show some self-explanatory examples.

Strand shell thicknesses, local heat flux density, slab surface temperatures and integral heat flux density of the four mould plates are shown in Figure 3. Several smaller graphics show the data at various mould positions. This allows for instance to compare the copper plate temperatures on broad and narrow faces along the mould length. Figure 4 exemplary shows a position 20 mm below the meniscus. Impact of plate temperature on slag film thickness is plain to see. From known slab surface temperature and break-point of liquid slag the differentiation into solidified and liquid fraction of the slag film layer is provided.

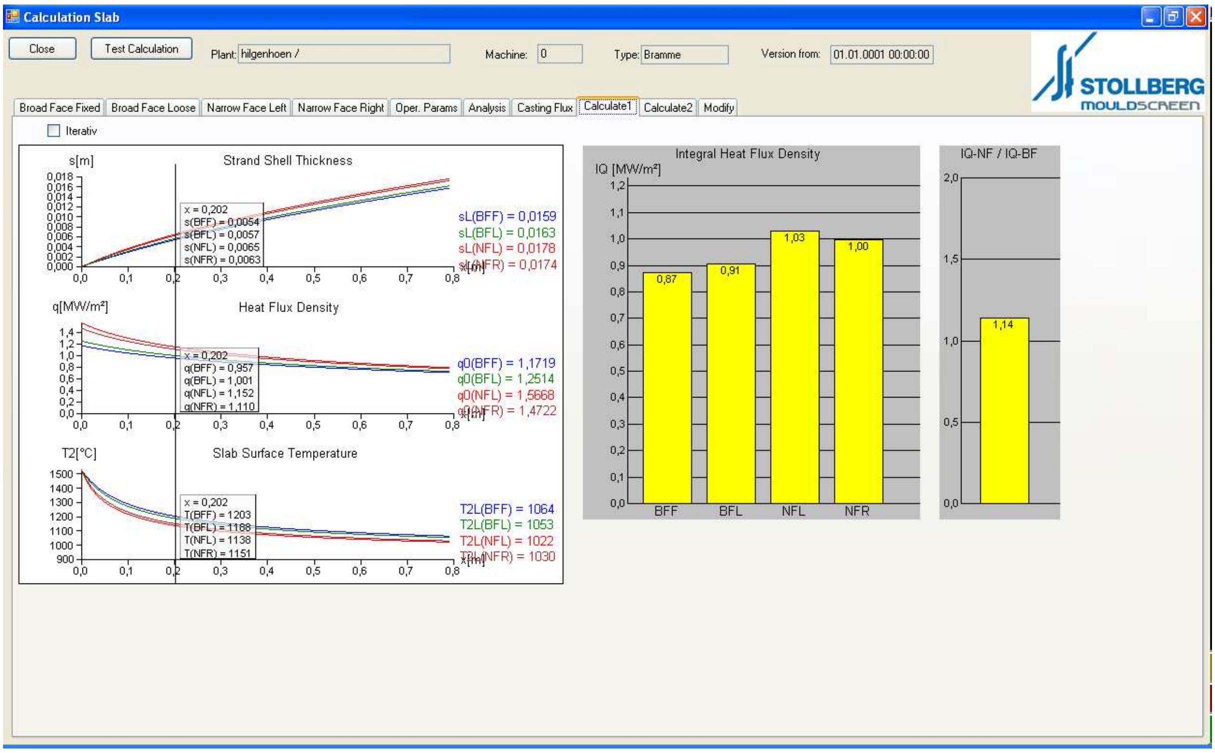


**Figure 3:** Strand shell thickness, heat flux density and slab surface temperature.

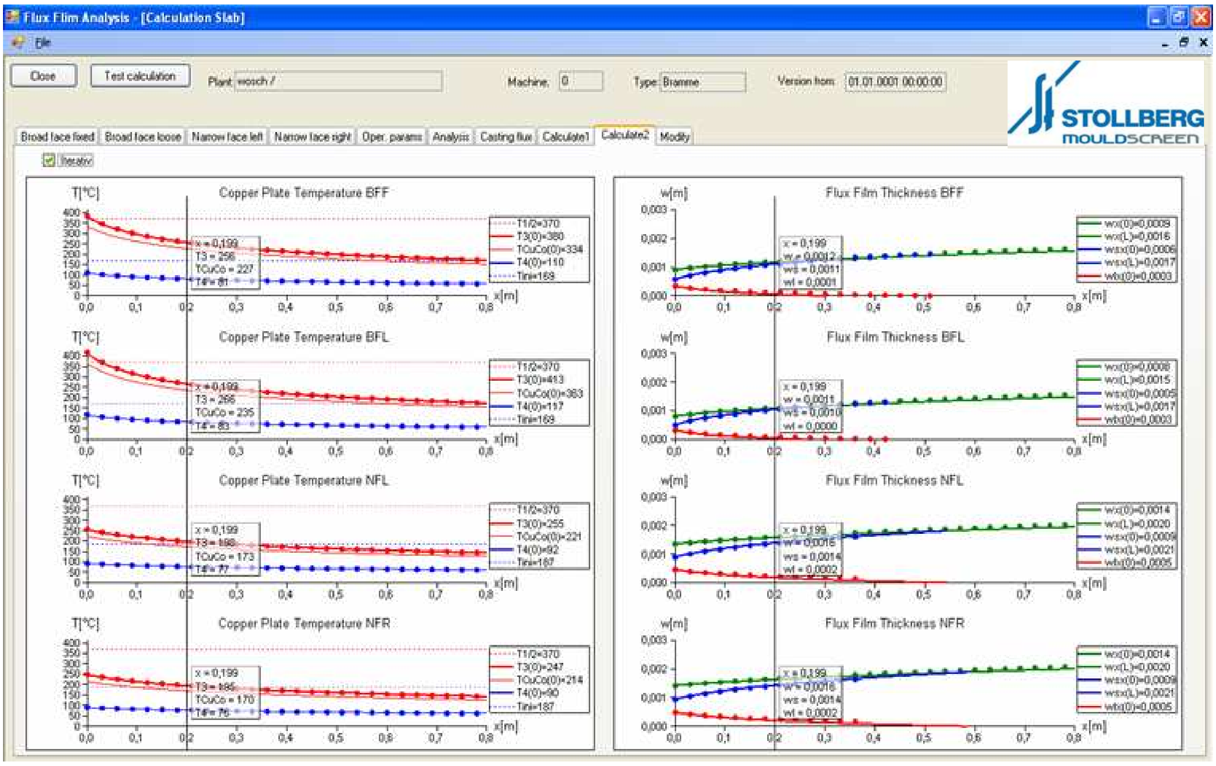


**Figure 4:** Copper plate temperatures and slag film thickness.

A special advantage of analytical modelling and resulting mathematical formulation of the physical relations is its easy application on parameter studies and inverse modelling. The question: "What happens, if …?" can be answered significantly quicker and more precise by analytical modelling than by any other way. Figures 5 and 6, right, shows the influence of casting speed on the liquid and the solid fraction of the slag film layer.

Changes of casting speed can be simulated by moving a slide bar and results directly appear on the screen. Conditions at the four mould plates are visualized directly. The corresponding copper plate temperatures are displayed on the left of each of the figures.

This modify-tool of MOULDSCREEN® represents a novelty concerning the way of looking at casting flux behaviour in continuous casting. For the first time ever the visualization of essential information on slag film behaviour during casting process is realized under varying operation parameters of a continuous casting machine. Besides casting speed several other factors play a certain roll when discussing about the slag film behaviour, e.g. water quantities, water flow temperature, water pressure, coating material and its layer thickness, copper plate material and thickness and casting flux type. Therefore, the modify-tool offers the chance to vary the above parameters (please refer to Box Properties/Change – upper left part in Figures 5 and 6).

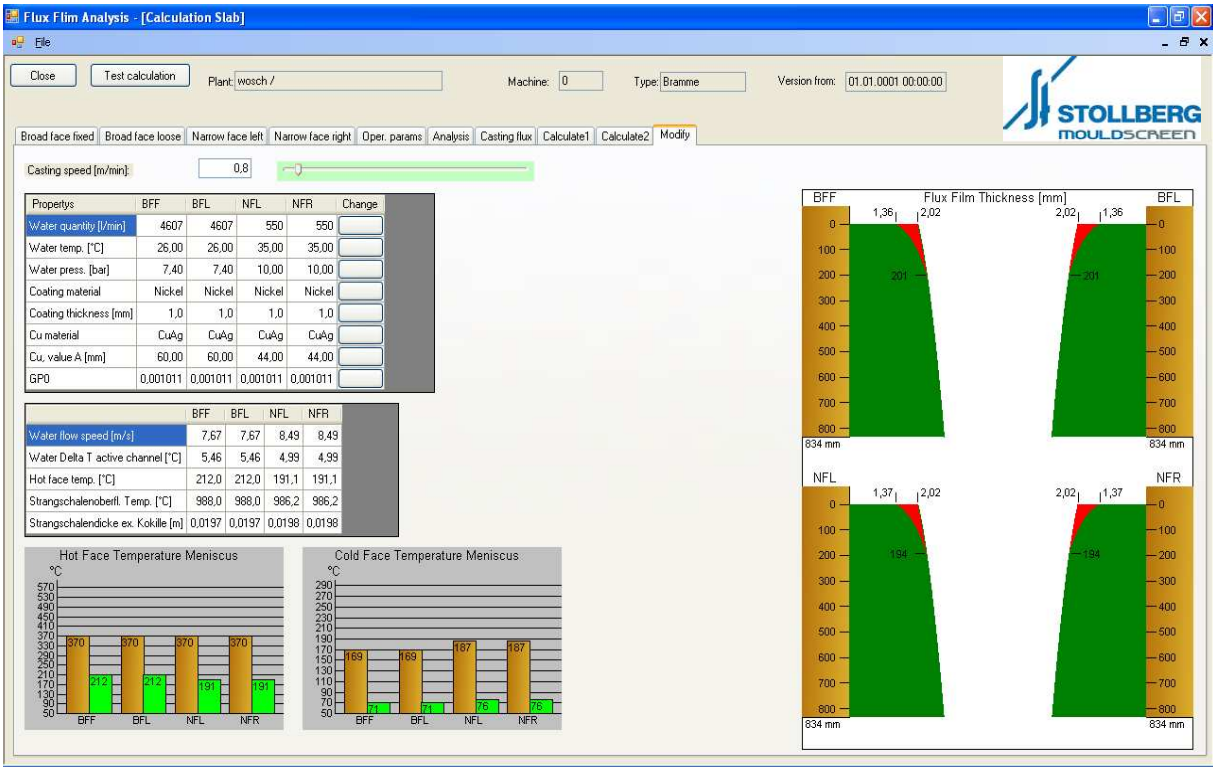


**Figure 5:** Modify tool: variation of operation parameters and its influence on copper plate temperatures and liquid/solid slag film thickness (red/green), e.g. Casting speed: 0.8 m/min (5 a) → 2.0 m/min (5 b)

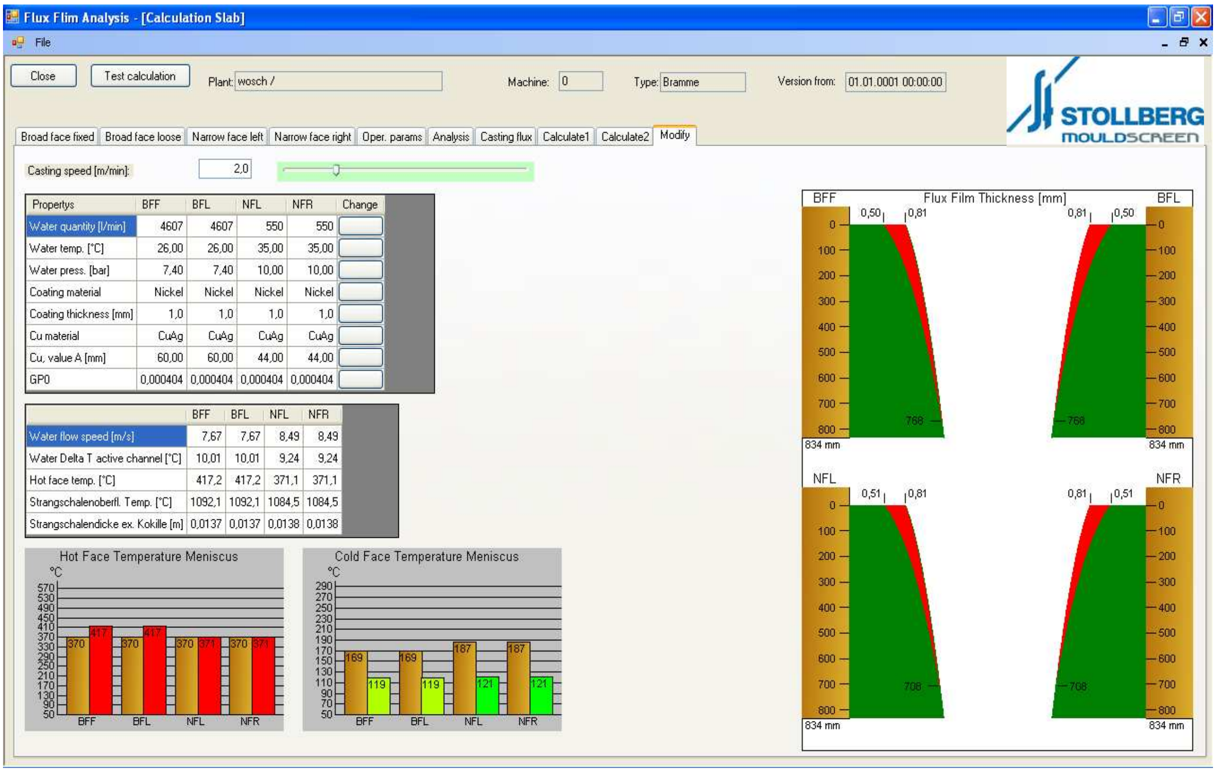


**Figure 6:** Modify tool: variation of operation parameters and its influence on copper plate temperatures and liquid/solid slag film thickness (red/green), e.g. Casting speed: 0.8 m/min (5 a) → 2.0 m/min (5 b).

## Comparative Studies via MOULDSCREEN®

Process optimization considering operation conditions and construction characteristics of various continuous casting moulds of our customers requires the analysis of process status and comparative studies. For this reason the MOULDSCREEN® algorithm has already been applied for evaluation of about 1000 slab and thin slab data sets. Some interesting results shall be explained during following pages.

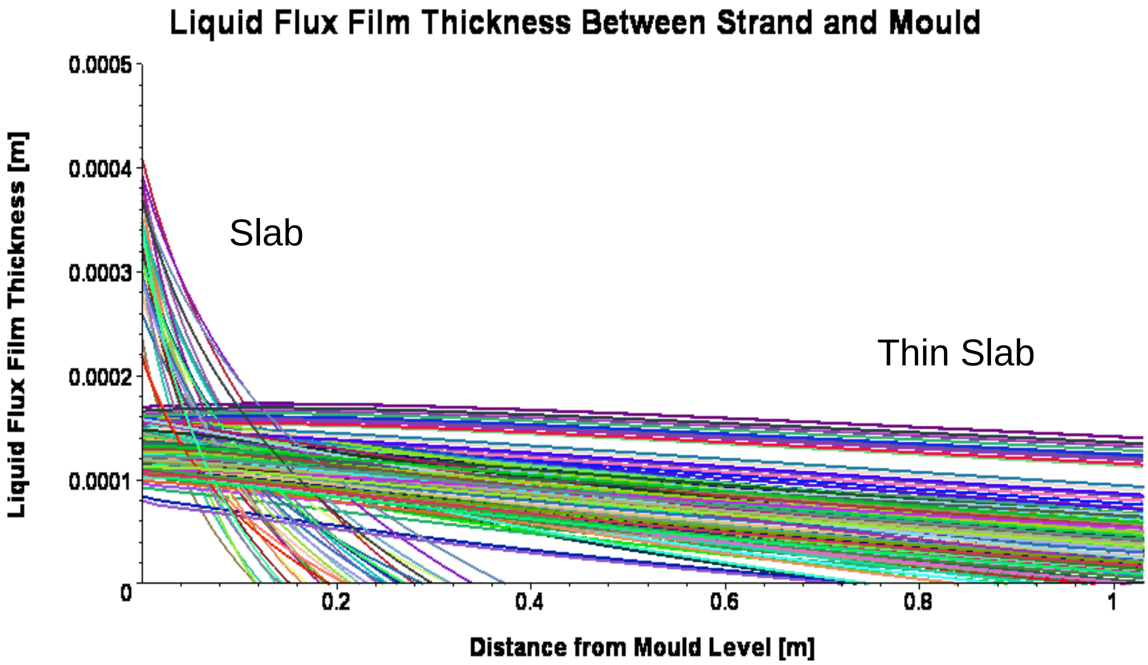


**Figure 7:** Liquid slag film thickness from mould level to mould exit of slab- and thin slab-casters, 300 caster data sets.

Figure 7 indicates the difference between slab and thin slab moulds. Slab machines show a much thicker liquid slag film at meniscus area. Thin slab machines show a significantly deeper penetration of the liquid layer along the mould length. In this context, the various casting speeds and temperature levels within the slag film of both caster types play a decisive roll. In the meniscus area there is solidified slag film at the mould plate and liquid slag film towards the new born strand shell.
Depending on break temperature of the flux and the gradient of slab surface temperature along the mould length, slower casting slab machines show only solid slag at the lower part of the mould, whereas faster casting thin slab machines show a liquid fraction of the slag film up to the very bottom of the mould.
At the point where slab surface temperature drops below break temperature, the liquid slag pool ends. So from application of MOULDSCREEN® you gain information about the lubricating conditions at the quality decisive upper range of the mould. During development of the theoretical basics of the model, a need for preferably simple mathematical formula arose, describing the relation between operating parameters of a continuous casting mould and the behaviour of the slag film. During the course of considerations it could be shown that the heat transfer resistance within the slag film has a linear dependence of the strand shell heat transfer resistance. This surprising result casually could be explained by the assumption that also the

liquid slag transported into the mould partly solidifies between mould wall and strand shall. Figure 8 shows this event for some operating parameters.

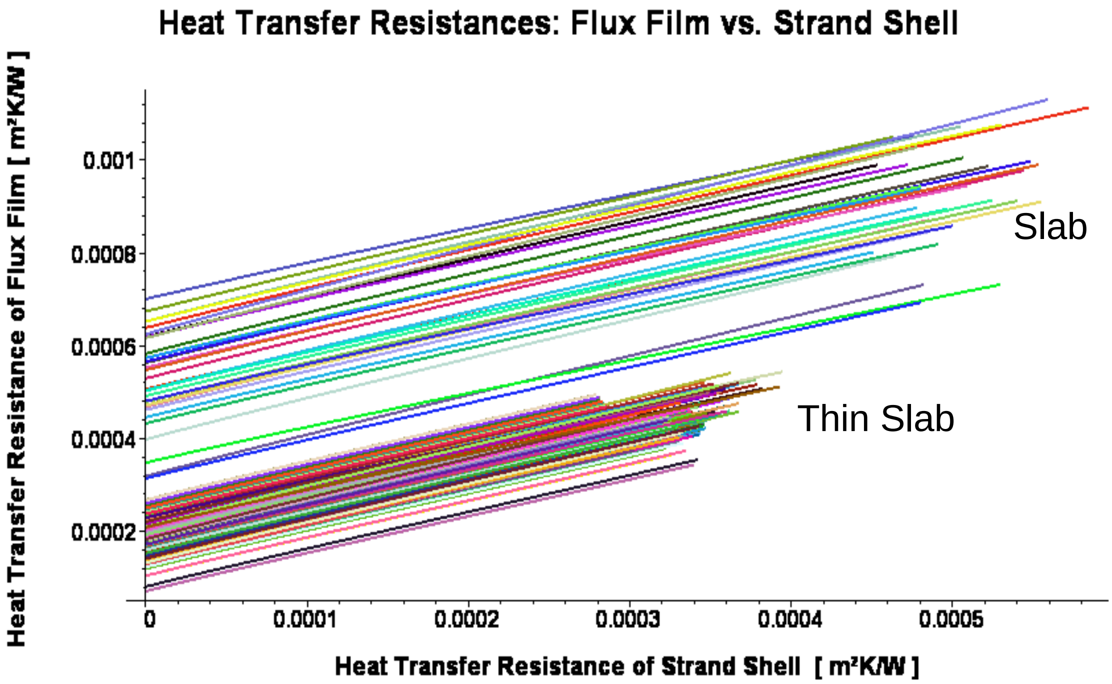


**Figure 8:** Linear relation between the heat transfer resistance of the slag film and the heat transfer resistance of the strand shell, 300 caster data sets .

Very often evaluating the operation conditions by primary process information (such as steel quality, cast width, mould length, casting speed, water quantity, water temperatures, etc.) does not lead to reliable and satisfactory characterization of the casting process. This especially concerns operational reliability, product quality and productivity.

A new approach to improve the situation is the use secondary process information, sourced deeply in physics of continuous casting (such as strand shell thickness, temperature field of strand shell, local heat flux density, copper plate temperature, heat transfer resistance in the gap, solid and liquid phase share of slag film). Information not visible from primary operation data is plain to see from secondary information. While primary information can be considered to be more or less measured values, the secondary information from physical knowledge depict more universal characteristics of the continuous casting process.

A new method to classify operation conditions of continuous casting moulds results from the MOULDSCREEN® investigations regarding the thermal conditions at the meniscus area.  Here, three non-dimensional parameters can be defined which are not correlated with casting speed and which spread around characteristic values in form of Gauß-distribution. That means that the thermal conditions at the meniscus of each and every mould could be described by three figures. They shall be named ternary meniscus parameter $p_1$, $p_2$ und $p_3$, and are shown in Figure 9. To centre the condition points in the middle of the ternary diagram, each parameter has been associated to a weighting factor $\beta_i$.

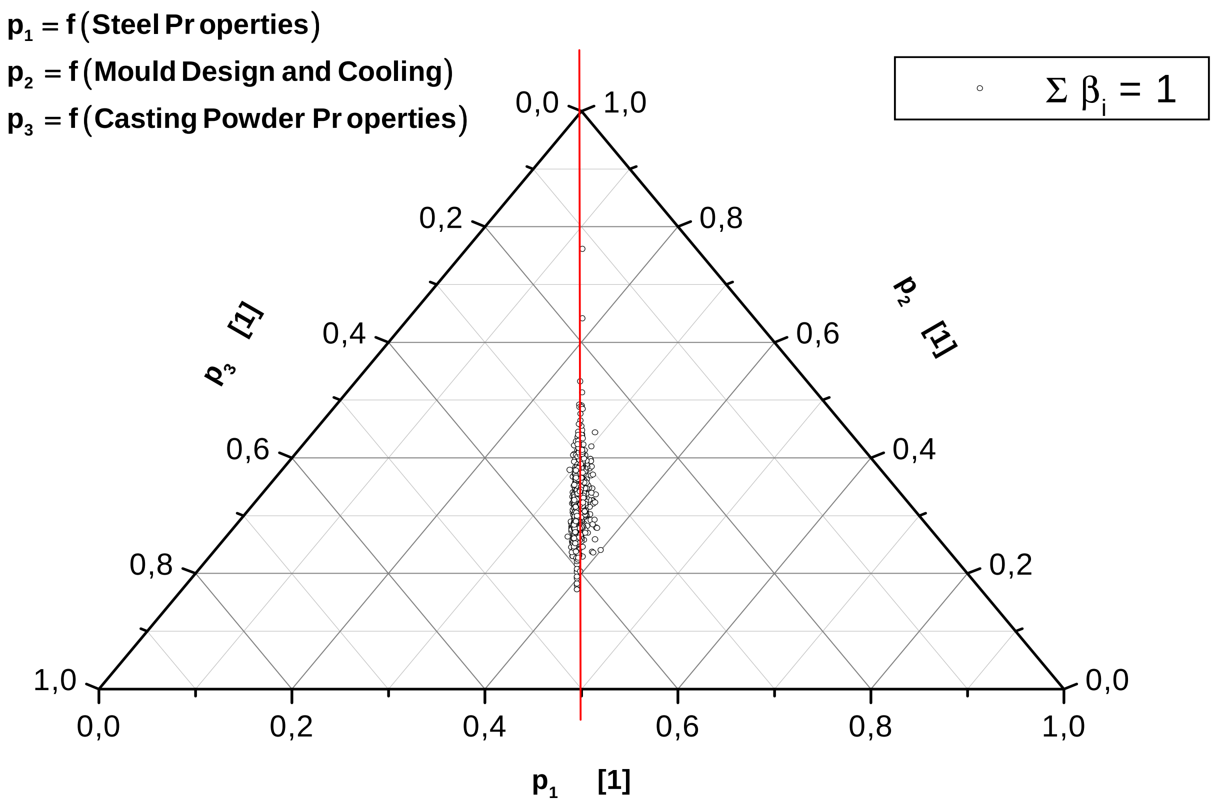


**Figure 9:** Ternary diagram of the three non-dimensional meniscus parameters $p_1$, $p_2$ and $p_3$, about 1000 caster data sets.

As you can see from Figure 9, condition points of all investigated casting machines are located around a vertical line inside the ternary meniscus parameter diagram, the highest concentration lying in the centre. Scattering around the symmetrical axis is quite small. This leads to the assumption that apparently there is a strong formal connection between $p_1$, $p_2$ und $p_3$ and that realistically only one factor would be needed for any characterization. In Figure 10 the factor is named with the symbol w. All casting speeds (slab and thin slab) are located inside the chosen band around w=1. Whether or not optimal casting conditions do exist in the centre of the ternary meniscus parameter diagram, is subject of present research and shall be discussed separately.

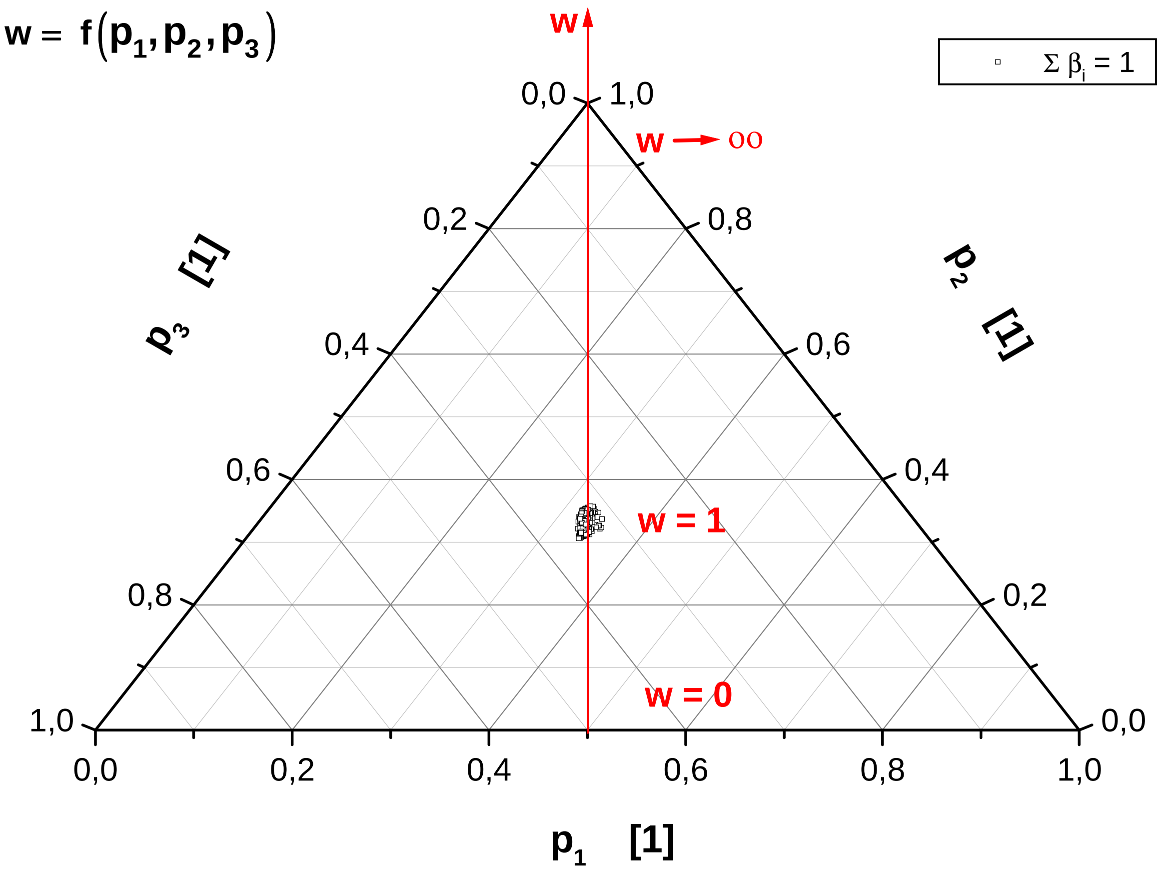


**Figure 10:** Selection of 300 central range points of the ternary non-dimensional meniscus parameter diagram including slab and thin slab data.

## Summary

On the basis of a mathematic-physical description of the thermal processes inside of continuous casting moulds, a software-tool has been developed in order to visualize the layer thickness of slag films between strand shell and copper plate. The tool by the name of MOULDSCREEN®, available for customers of S&B Industrial Minerals GmbH, Stollberg Division, distinguishes between the liquid and the solidified slag layer in continuous casting moulds. It additionally calculates all relevant factors, such as strand shell thickness, heat flux density as well as slab and copper plate temperatures as a function of location. Depending on data availability, visualization of all mould faces is provided.

The modify-tool of MOULDSCREEN® is capable of analyzing various operating scenarios for a given mould and displays the results via mouse-click to a computer screen. This allows direct evaluation of the casting process under variation of casting powder characteristics or changes to casting speed, water quantity, water temperature, pressure, copper material and thickness, coating material and thickness.

The algorithm of MOULDSCREEN® can also be applied for comparison purposes of various operating conditions and construction characteristics of continuous casting moulds. The evaluation of numerous mould operation data within short periods of time delivers new information about interdependencies and options for process optimization. Also new is the classification of thermal conditions in the meniscus area in form of a ternary parameter diagram. Thereby MOULDSCREEN® provides chances to better characterize and evaluate the meniscus area as a critical region regarding cast product quality and process reliability.

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