Numerical investigations of influences on the flow in a vertical twin roll strip caster for stainless steel

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Twin roll strip casting is a near net shape method for the production of metal sheets directly from the liquid phase. The thickness of the strips is in the range of several millimeters. One benefit of this method is the short length of the plant and the large saving of energy, because there is no need for reheating and milling of the steel. This results in lower costs in comparison to conventional continuous casting.
Because of the high casting speeds in the range of 1 m/s and the thin shape of the product, the flow and the heat distribution inside of the casting pool are crucial for a successful process and the quality of the strip.
The flow was earlier investigated in a full-scale water model of a twin roll strip caster in industrial scale, where a modular submerged entry nozzle was successfully used to create different flow regimes inside of the pool.
To take the influence of the heat distribution and the solidification into account, the process was numerically simulated with Ansys Fluent. The surface-motion of the pool, especially the shape of the meniscus, is also very important for the strip formation, because the thickness of the strip is directly addicted to the contact length.
Due to the transient nature of the turbulent, multiphase, non-isothermal fluid flow problem with solidification within strongly changing cross-sections, the modelling is a complex task. The VOF-method is implemented to capture the multiphase flow. Furthermore the solidification is modelled using an enthalpy-porosity method.

KEYWORDS: TWIN-ROLL STRIP CASTING - NUMERICAL SIMULATION - STAINLESS STEEL - DIRECT STRIP CASTING - DSC - NEAR-NET SHAPE METHOD

INTRODUCTION

The stainless steel production has experienced a steady evolution in the last decades. These developments led from the ingot casting to the establishment of more near net shape productions, such as the continuous casting. In case of the continuous casting there was the invention of the CSP-mold, which further decreased the contour of the casting goods and resulted in less steps of reheating and rolling. The consequent advancement was the direct strip casting of metals (DSC). This category includes several different processes, which all have the same task: the production of metal sheets directly from the liquid phase. One of those processes is the vertical twin roll strip casting, which will be treated in this work. The idea for it already came from Sir Henry Bessemer in the 19th century. Though, it took more than one century to make this process technically realizable. The reason for that are the high casting speeds in the range of 60 m/min and the short solidification times, which are less than one second, so this process has high demands on the control technology [1]. The benefit of the twin roll strip casting is the high potential of saving energy and costs in comparison to the conventional production. According to Walter et al the energy consumption and by that the amount of CO2-emmissions can be reduced by up to 85 % [2]. The strip thickness is in the range of 1-10 mm [1,2]. For other materials like copper and aluminum, methods for strip production have been established, like the hazelett® caster. The large difference of the stainless steel production is the operating temperature, which is significantly higher. Despite the higher requirements, resulting of the boundary conditions, CASTRIP® built plants for commercial production [3-4].

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Due to the small volume of the casting pool between the casting rolls and the high casting speed, compared to conventional continuous casting, the flow has a large influence on the quality and the stability [5]. The flow can cause inhomogeneous temperature distributions across the width of the strip, which can result in differences of the strip thickness or even a failure of the process [6]. That for the process is often simulated by the use of water models. For example Bouchard [7] investigated the influence of immersion depth, flow-rate and pool height for different nozzle designs, by the use of ultrasonic detectors, video monitoring and residence time distribution (RTD) in a full scale water model. It showed that the nozzle design has an influence on the flow. The research of Wang et al. was also focused on level fluctuations and RTD. In Addition he performed numerical simulations to visualize the flow inside the pool [8]. In this work a modular submerged entry nozzles (SEN) was investigated. Unlike conventional SENs it consists of five chambers, each supplied by a separate inlet. This allows to control the mass-flow through all immersed faces of the SEN, Figure 1.

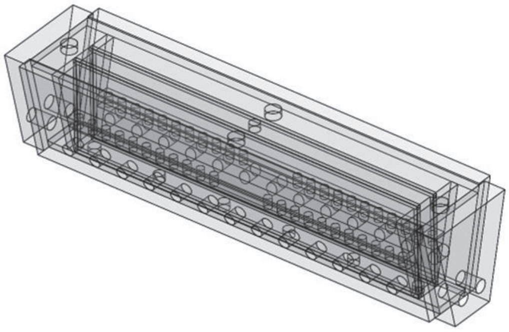

Fig. 1 - Modular SEN

NUMERICAL SETUP

Assuming a symmetric behavior of the flow, a twofold symmetric mesh of the twin roll strip caster was modeled to perform the calculations. The model also includes the casting roll, as can be seen in Figure 2. The faces, which are colored yellow, mark the symmetry planes of the mesh. In this case a hybrid mesh, made with Ansys ICEM®, was used, where the part of the submerged entry nozzle (SEN) was modeled by an unstructured mesh. The rest of the model is structured. The amount of cells is about 1.3 million.

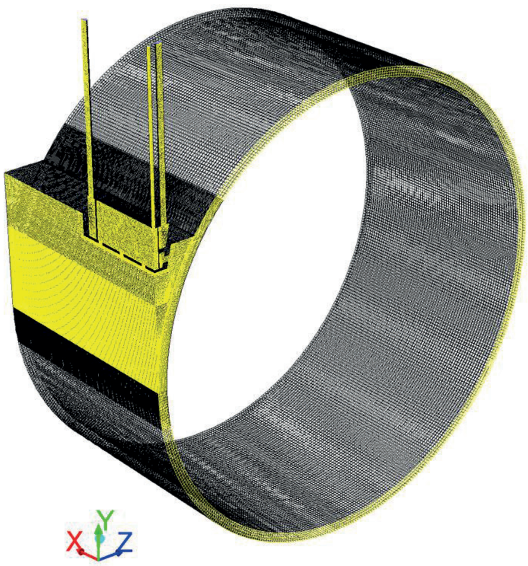

Fig. 2 - Quarter Mesh of the twin roll strip caster

The Dimensions of the simulated strip casting plant are according to industrial scale [1] and are listed in Table 1.

Tab. 1 - Plant parameters

Parameter	Value	Unit
Roll-width	1400	mm
Roll-diameter	1500	mm
Mass-flow	28	kg/s
Casting-speed	0.95	m/s
Strip-thickness	3	mm

For the modeling of the turbulence the k-omega-SST model was used. The solidification was modeled with a porosity-enthalpy-approach. This method treats the liquid as a porous media in the mushy-zone. Thereby the porosity is dependent of the liquid fraction. The liquid fraction in the interval between solidus and liquidus-temperature is calculated in the following manner:

$$\begin{aligned} &\beta = 1 \quad \text{for} \quad T > T_{liq} \\ &\beta = 0 \quad \text{for} \quad T < T_{sol} \\ &\beta = \frac{T - T_{sol}}{T_{liq} - T_{sol}} \quad \text{for} \quad T_{sol} < T < T_{liq} \end{aligned} \qquad (1)$$

The liquid fraction β describes the amount of liquid phase for every single cell of the volume.

The porosity of the cell corresponds to the liquid fraction. According to that, a completely solidified cell has a porosity of zero, which results in a flow velocity of zero as well. As a consequence of the reduction of the porosity, a momentum sink occurs, which is of the following form:

$$S = \frac{(1-\beta)^2}{(\beta^3 - \varepsilon)} A_{mush} (\vec{v} - \vec{v}_p) \qquad (2)$$

The mushy-zone parameter A_{mush}, is equal to the permeability. It can be derived by the Kozeny-Carman equation, which describes the pressure loss of fluids streaming through fine-grained beds. Based on these assumptions the permeability in this case is A_{mush} = 1.21e8.

As described earlier the solidified volumes no longer have a flow-velocity. However, since we consider a continuous casting process in the present case, the fluid, which solidified on the casting rolls moves with casting speed. So the proper values were patched for the pull-velocities, which describe the movement of the solidified volumes.

Due to the steady calculations showed problems according to the stability, a pseudo-transient strategy was applied. This was possible because the process itself runs in a steady state and the time-history of the development of the flow and heat distribution is not of interest.

The heat which has to be dissipated can be evaluated as follows:

$$H = h + \Delta H_{lat} \qquad \text{with} \qquad h = h_{ref} + \int_{T_{ref}}^{T} c_p dT \qquad (3)$$

For a proper simulation of the heat distribution inside of the casting roll, the rotation must be taken into account. That for the moving reference frame-approach was utilized. This approach allows to treat the roll motion and the resulting heat distribution, which usually leads to an unsteady problem, as a steady-state case. For the simulation of the free surface of the pool the Volume of Fluid model (VoF) was used. This multiphase model is an Euler-Euler approach which is based on the tracking of the interface of the different phases. This approach is suitable for the calculation of two or more immiscible fluids. In addition to the momentum equations the volume fraction c of each phase has to be calculated in every cell. The sum of the volume fractions of all phases results in one for every cell. Assuming the volume fraction of the q^{th} fluid is c_q, this leads to three possible cases in each cell. The case $c_q = 0$ means there is no fluid of phase q in the cell. If $c_q = 1$ the according cell is completely filled with the q^{th} fluid. The last case, $0 < c_q < 1$, means, that this cell includes the interface between fluid q and at least one other phase. The surface of the interface was interpolated by using the geometric reconstruction scheme.
The free surface, which was calculated by the VoF-method, was compared to a surface-shape which was determined from the pressure distribution on the pool-surface from a single phase simulation. The latter approach thus results in much shorter calculation times. The according surface heights were calculated from the following equation:

$$\Delta h = \frac{p_{stat} - \bar{p}_{stat}}{(\rho_{liq} - \rho_{gas}) \cdot g} \qquad (4)$$

Boundary Conditions
The treated material is a stainless and acid resistant steel of the grade 1.4301. The material properties of the liquid steel, which were used for the simulations, can be found in Table 2.

Tab. 2 - Material properties of 1.4301

Parameter	Value	Unit
Liquidus-temperature	1740	K
Solidus-temperature	1710	K
Specific heat capacity	795	J/(kg*K)
Density	7000	kg/m³
Dynamic viscosity	f(T)	Pa*s

The casting-roll was modeled as a water-cooled cooper roll with a thickness of 30 mm. The according material properties of solid copper are listed in Table 3.

Tab. 3 - Material properties of copper

Parameter	Value	Unit
Density	8978	kg/m³
Specific heat capacity	381	J/(kg*K)
Thermal conductivity	387.6	W/(m*K)

As already was mentioned, only a quarter of the strip-casting-plant was modeled for the simulations, assuming a dual-symmetric behavior of the flow. This results in a much smaller amount of cells and by that in faster calculations The free top surface of the melt-pool was modeled as a flat frictionless wall for the single-phase simulations. Considering the heat losses towards the upper surrounding of the liquid pool a heat flux of 75 kW/m² was set at the pool surface. For the heat transfer coefficient from the melt pool to the roll surface a constant value of 8000 W/m²K was set. This results in a heat flux, which is sufficiently high enough to compensate the sensible enthalpy and the latent enthalpy. Figure 3 shows a schematic view of the heat transfer from the liquid metal through the casting roll into the cooling water.

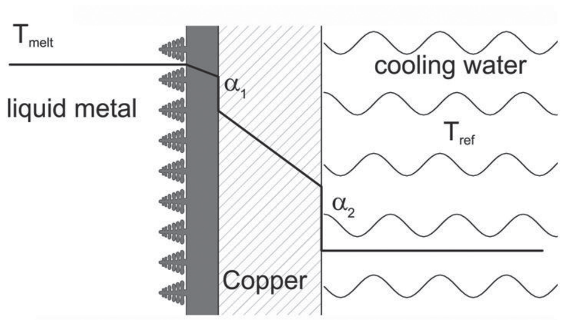

Fig. 3 - Schematic heat transport from the melt to the cooling water

Table 4 shows the corresponding values for the heat transfer from the liquid metal to the cooling water.

Tab. 4 - Heat transfer parameters

Parameter		Value	Unit
Melt to roll	α_1	8000	W/(m²*K)
Roll to water	α_2	40000	W/(m²*K)
	T_{ref}	300	K
Melt to side-dam	α	200	W/(m²*K)
	T_{ref}	1300	K
Free surface heat flux		75000	W/m²

Under the assumption, that the metal leaves the melting pool as a completely solidified strip, the outlet at the casting gap, which is at the tightest spot between the rolls, was set to velocity outlet. The velocity was set to casting speed.
As can be seen from Figure 1, the used SEN is designed with

several inlets. This allows to control the mass-flow through each chamber of the SEN. In this work two different mass-flow-inlet-combinations were investigated. The total mass flow is held constant through all simulations, at about 7 kg/s for the quarter-mesh model. In Table 5 the simulated combinations are listed.

Tab. 5 - Investigated mass flow combinations

case	Front [kg/s]	Long [kg/s]	Bottom [kg/s]
1	1.15	5.83	0
2	5.83	1.15	0

The above listed flow combinations were chosen from previous investigations, where they showed varying flow patterns.
For the calculation of the surface motion, the multiphase simulations were performed for water as liquid so far. This was done, because the surface motion was also investigated in a full scale water model of the facility. So it is possible to validate the simulations of the free surface.

RESULTS

The numerical simulations showed a large influence of the solidification process on the formation of the flow regimes inside of the melt pool. A direct comparison of the isothermal and the non-isothermal flow for the case 2 is shown in Fig. 4 for the symmetry-z-plane. On the left of the planes is the symmetry x-plane and on the right the side-dams. While the flow regime in the isothermal calculation shows a homogeneous distributed flow across the complete section, it seems that the non-isothermal flow is suppressed to the upper right of the plane. The result is a distinct flow-field. The isothermal flow for this case is relatively uniform, except the areas at the outlet and right next to the SEN. This region show higher velocities. The high velocity at the outlet results from the boundary condition at the outlet, which specifies a velocity of 0.95 m/s downwards. Right next to the SEN is also a section, where the velocity is 1 m/s or higher. This results from the penetrating free jet from the front side of the modular SEN which has a high mass-flow rate in this case. This jet also creates a high velocity in the case of the non-isothermal calculation. The rest of the flow field shows distinctly lower values for the velocity.

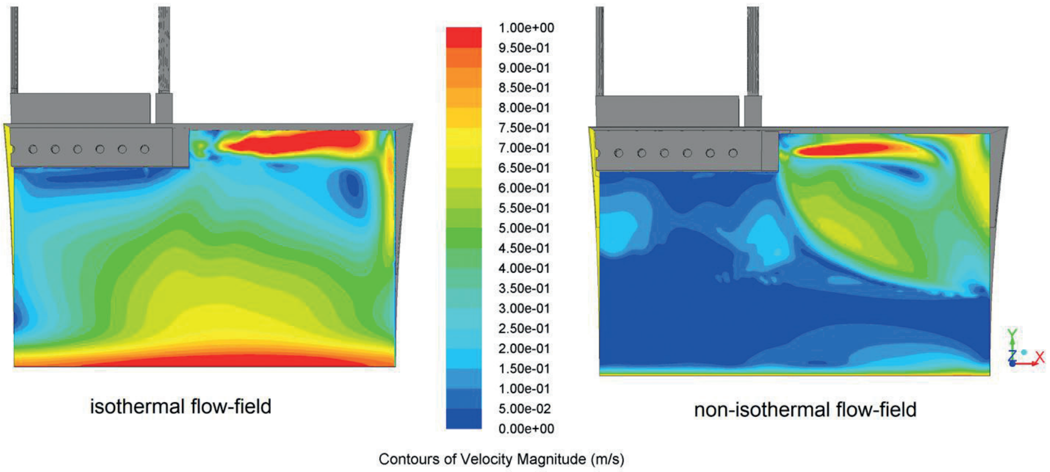

Fig. 4 - Comparison of isothermal and non-isothermal flow for flow-case 2

Also it became obvious, that the temperature distribution over the strip-width is also influenced by the chosen flow combination at the SEN. As can be seen from the shown isothermal surfaces at liquidus-temperature (T = 1740 K, colored red in Fig. 5), the shape is strongly influenced by the applied flow. It is recognizable, that the liquidus-surface extends deeper into the pool in areas, where the SEN has a higher mass-flow-rate.

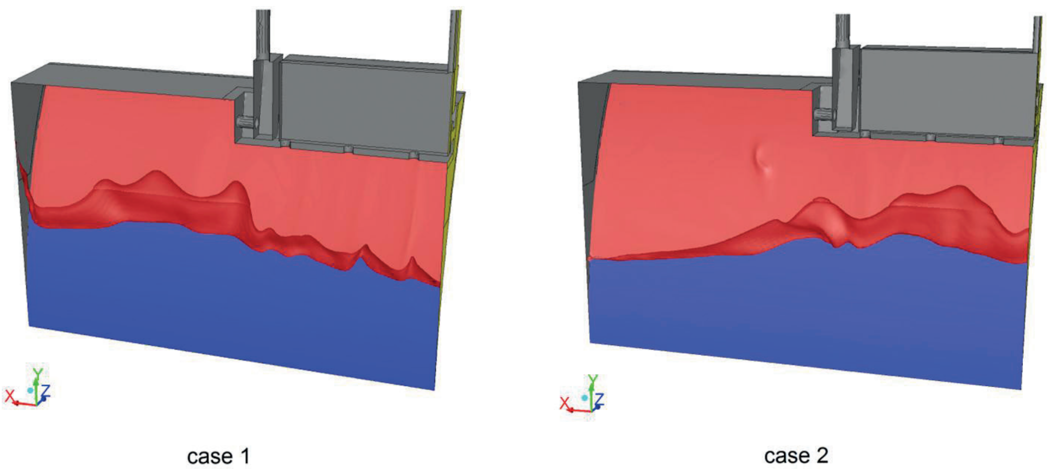

Fig. 5 - Comparison of the liquidus-surfaces (colored in red) of case 1 and 2

The short metallurgical length and the high rate of the process prevent, that this uneven liquidus-surface, which equals an inhomogeneous temperature-distribution across the width, is compensated before the steel arrives the casting gap and leaves the pool. Fig. 6 shows the plot of the temperature over the strip width at the surface of the solidified strip in the casting-gap. The progress of the temperatures corresponds to the shape of the liquidus-surfaces in Fig. 5. For the case 1 this results in a higher temperature in the center area of the strip beneath the SEN between 0.0 m< x< 0.3 m, caused by the high mass-flow through the long-chambers of the SEN. Vice versa the temperature for case 2 increases towards the side-dam of the pool at x = 0.7 m.

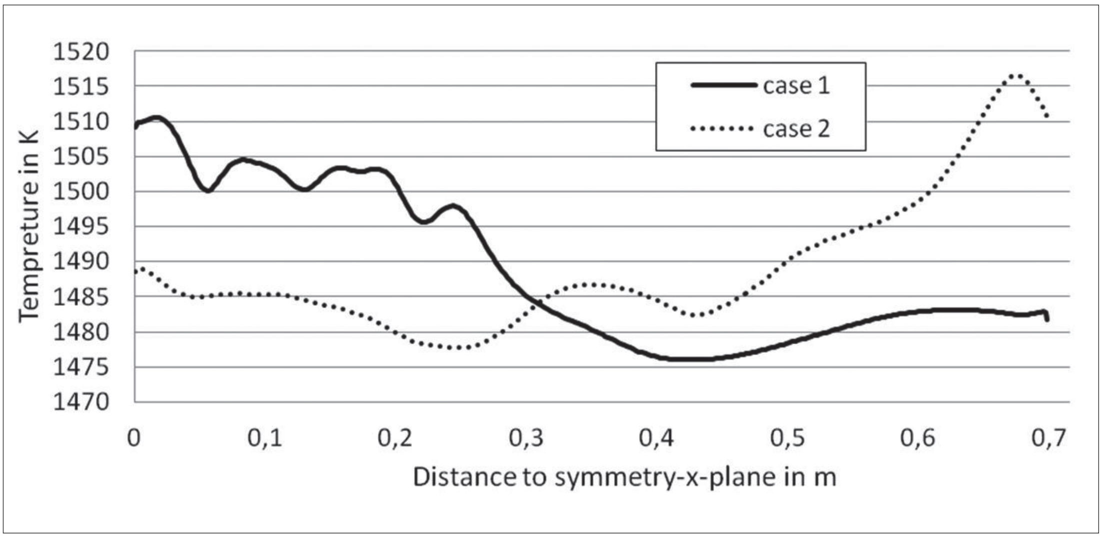

Fig. 6 - Temperature distribution at the contact-line of solidified strip and casting roll at the casting gap for case 1 and 2

The free surface was simulated with the VoF approach. Fig. 7 shows the averaged formation of the free surface for case 1. In front of the long chamber of the SEN on the left side of the picture an elevation can be seen, which is caused by the high mass-flow through the long chamber. The rest of the free surface is relatively calm and even.

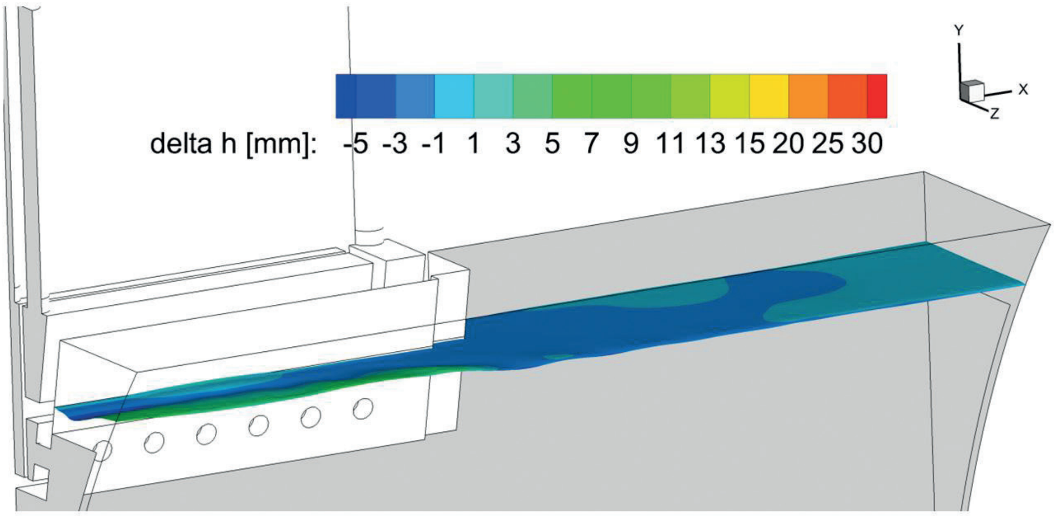

Fig. 7 - VoF Simulation of the free surface for case 1

Fig. 8 shows the same free surface of the pool, which was calculated by the equation (4). It can be seen, that the same evaluation right in front of the long chamber is calculated. The rest of the surface shows a good agreement between the two methods.

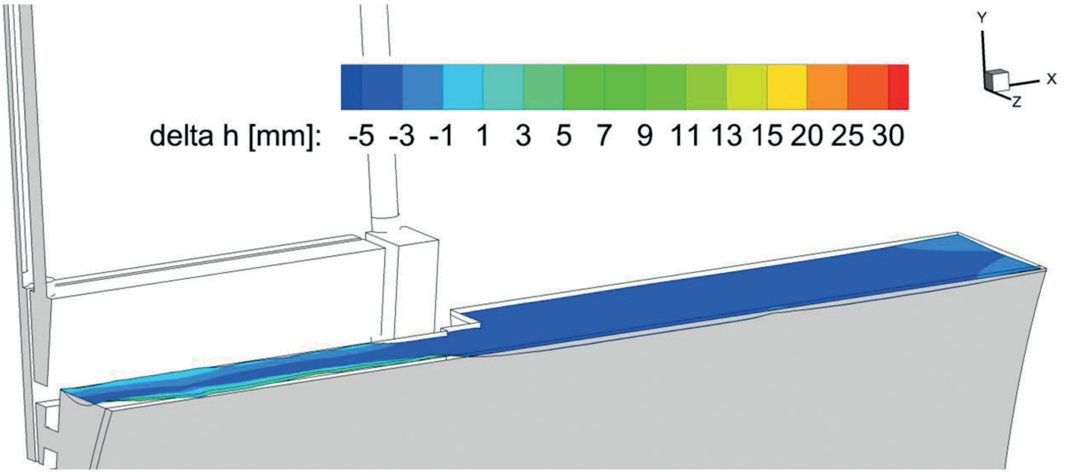

Fig. 8 - Free surface for case 1 calculated from the pressure distribution

CONCLUSION

The performed simulations showed that the flow field has a distinct influence on the distribution of the heat inside the pool and by that affects the formation of the mushy-zone. The shape of the liquidus-surface influences the flow regime in return, by limiting the available volume for the free development of the flow. So there is a bilateral affectation between the flow and the heat distribution, which makes non-isothermal numerical simulations necessary. Also it was shown that the temperature distribution along the strip width depends on the flow. So the formation of the shape of the mushy-zone predicts the temperature-behavior at the casting gap.

To reach a homogeneous temperature-distribution across the strip width a suitable feeding system is crucial to get a uniform flow. Also it became obvious, that none of the two investigated flow-combinations shows an even temperature-shape at the casting gap.

The research according the free surface simulations in the pool showed that the calculation of the height from the static pressure distribution on the surface is in good accordance to the VOF-simulations. This allows making qualitatively predictions about the pool level fluctuations from the single-phase-simulations with no need of transient multi-phase simulations.

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