Integrated numerical simulation of the industrial continuous casting process

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Abstract. The production of a continuously cast strand involves a large number of coupled phenomena involving flow, heat transfer, solidification and thermo-mechanics. In this paper, different approaches are described for the numerical modelling of industrial continuous casting processes at different levels of detail, dependent on the questions to be investigated. In the simplest case to obtain a rough estimate of the process conditions, the solidification of the strand is considered with a prescribed convective flux profile in the strand body based on the withdrawal speed. In the most complicated case, the process phase of filling of the empty mould is first calculated, followed by the phase of the withdrawal of the strand including consideration of the flow in both strand and tundish.

1. Introduction
Modelling continuous casting is as complex as the process itself. In order to achieve a robust model for industrial application with acceptable calculation times, the handling of the changing of boundary conditions at the inlet and free surface of the metal are important. As an example, one can simplify the handling of the melt free surface in the tundish, launder and boundary conditions for the fluid flow. This can be used to significantly speed up the fluid flow computations, due to the long duration of the withdrawal phase. Although it is possible to continue to consider the free surface in the withdrawal phase, for the copper and aluminium applications shown in this paper experience has shown that this is not necessarily required.

The handling of the momentum equations in the moving strand and the remaining liquid pool during withdrawal by using two different coordinate systems will be discussed. A special enhancement is applied in the predictor step of the PISO method for the incompressible flow in order to account for the simultaneous treatment of fluid flow in two different coordinate systems.

1.1. Solidification simulation with prescribed convective flux
The first and easiest approach is a thermal simulation with a prescribed convective flux as a block profile in the strand body, see figure 1(a). In that case, the enthalpy equation is solved and no velocities in the liquid regions have to be calculated. The convective flux is unidirectional with a value given by the casting speed. The casting speed can be defined time dependent. Typical results can show the temperature distributions and the corresponding liquid pool depth. Additionally, the thermal criteria like thermal gradient, cooling rate, solidification time and microporosity are calculated. The flow effects on these criteria and on the temperature distribution are very simplified, but it can nonetheless be useful for a first rough estimation of the process conditions for primary
and secondary cooling, in order to verify the defined boundary conditions and heat transfer coefficients between applied materials.

![Figure 1](image)

**Figure 1.** Two different approaches to continuous casting process modelling. (a): most simplified without any fluid flow calculation, the block velocity profile is prescribed in the strand region for the convective heat flux. The temperature above the strand is fixed. (b): The withdrawal again starts with a filled volume over the strand, but the fluid flow is computed everywhere and the temperatures over the strand are not fixed. No melt free surface movement is considered as the volume over the strand is completely filled from the beginning.

1.2. **Fluid flow without filling of a tundish**

A more realistic representation of the entire process has to allow for the assessment of the flow conditions during start-up and subsequent strand withdrawal. The volume above the strand is taken as completely pre-filled at the beginning of the withdrawal process, see figure 1(b). The melt free surface is considered as fixed and coincident with the top of the domain/mould. A Dirichlet boundary condition for pressure is applied at the inlet while the outlet boundary condition is set at the bottom strand edge. Using this approach, the computation of the withdrawal starts immediately. The transient heat transfer during the filling of the mould is not considered, instead a homogeneous temperature is prescribed at the beginning of the calculation. In comparison to the first approach, it is now possible to calculate the forced and buoyancy driven melt flow with conjugate heat transfer, the latent heat release and solidification. The convective heat transfer will cause changes in the temperature distribution compared to the approach using a prescribed convective flux as in figure 1(a).

1.3. **Fully integrated approach including filling of the launder and tundish**

The most complex option considers a coupled thermal and flow simulation consisting of at least two subsequent process phases. The first phase is a classical mould filling with an empty mould at the beginning. The process is switched to the second phase of strand withdrawal, when a predefined control condition such as filling time or volume percent filled or the melt level in the mould is achieved. The modelling of the melt free surface and the control of the inlet melt flux can be also switched to a simplified approach (figure 2(a)) either at the start of withdrawal or during withdrawal when an analogous second switch condition is reached. In the first case, the computation of the melt free surface (figure 2(b)) is omitted. These algorithms are described in detail in the next chapter.
Figure 2. Phases of the integrated process model with fluid flow. (a) Filling of the empty volume over the strand and a part of the strand. (b) Withdrawal simultaneously with cavity filling. (c) The consideration of the melt free surface is terminated at the very beginning of withdrawal or in the withdrawal phase, because a nearly stationary state of the free surface may be expected. The melt free surface is smoothed, the inlet is transferred onto the location of the actual melt surface. The inlet flux is set equal to the mass flux given by the withdrawal velocity.

2. Modelling the continuous casting process

2.1. Fluid flow approach
The fluid flow in the continuous casting model is handled using the Finite Volume method [1] on a Cartesian grid. A staggered variable arrangement is used. The pressure is stored in the middle of the grid cell, while Cartesian velocity components are stored for each cell in the middle of its three faces in +X, +Y and +Z directions. The governing equations are assembled and solved in parallel using the MPI distributed memory approach with dynamic load balancing by means of grid partitioning into load balance units (LBU’s) [2]. The momentum and mass continuity equations are solved by the PISO method for incompressible flow [3]. The melt free surface is treated using the volume of fluid method (VOF) [4]. In this respect, the continuous casting model follows the concept of the commercial MAGMASOFT® software package for filling in shape casting processes [5]. A special treatment is needed to account for the melt flow in the moving strand volume during the withdrawal and for the additional heat sources there.

2.2. Solidified cells
The velocity of the solidified melt is usually set to zero in filling for shape casting processes. The continuous casting process is more complex. We continue to treat the solidified melt as stationary everywhere before the withdrawal starts. In the withdrawal phase, the solidified fraction can move freely as equiaxed crystals driven by the melt flow and their buoyancy, or can stick somewhere on the outside strand wall, or can be moved with the prescribed withdrawal velocity as a rigid body in case of columnar crystals. This causes a different relative velocity between the solid and liquid fractions. Here, the equiaxed crystals are not modelled directly as a substantive phase within the single-phase fluid flow model. The effective viscosity of the solidifying melt is modelled as an exponential function of the solid fraction.

A grid cell is considered as “solidified” if some critical fraction solid is reached. The solidified strand cells are moved with a prescribed withdrawal velocity. This means that the convective flux and the momentum diffusion between liquid and solid fractions have to be accounted for. This is done using two different reference coordinate frames, see figure 3(a).
Figure 3. (a) Logical subdivision into regions of strand and of the melt above it. The liquid and solid are dashed horizontally and inclined, respectively. Momentum equations are not solved in the solid. The used coordinate frames for the momentum and mass continuity equations are stationary $S_1$ outside the strand and $S_2$ moving with the withdrawal velocity in the strand. The grid cells at the $S_1/S_2$ interface and their velocity components are shown for the momentum predictor steps. (b) The velocity transformation into the moving reference frame $S_2$ precedes the predictor step for the interface cells in the strand. (c) The same for the cells over the strand region, the predictor step for them is preceded by the velocity transformation in the upper strand cells.

2.3. Momentum equations and mass continuity in withdrawal

Velocities at the beginning of the time step are given in the stationary coordinate frame $S_1$. Before the momentum predictor starts, velocities in the strand grid cells are transformed into the moving $S_2$ coordinates i.e. $V \rightarrow (V - V_{strand})$. Solidified cells have zero velocity in $S_2$, hence the relative velocity liquid-solid coincides with the transformed liquid velocity there and no changes are needed in the standard momentum diffusion formulation.

This procedure requires a special treatment of the $S_1/S_2$ interface. First, new momentum values are computed everywhere in the PISO predictor step. Next, corrections are done for the horizontal grid layers located directly at the $S_1/S_2$ interface. The predictor step is repeated for the selected top grid layer of the strand, see figure 3(b). The old velocity values of two bottom grid layers over the strand are transformed into the moving reference frame $S_2$. Next, the predictor step for the bottom grid layer over the strand is repeated. Again, old velocities in two top strand grid layers are transformed into $S_1$. Each new velocity value is now computed for the stencil velocities in the same coordinate frame. The same holds formally for the horizontal continuous casting setup, only the setup in figure 3 has to be rotated into the horizontal direction.

Velocities in the strand material are transformed back into the stationary $S_1$ at the end of each time step. They are used in the transport equations for conjugate heat transfer, in calculating criteria functions and, when desired, for the transport of chemical species and particle movement simulation.

A further implication of the two reference frame scheme is a need to adjust the pressure correction equation for the cells located at the interface over the strand, as the velocity at their bottom face is stored for the adjacent strand cell in the moving $S_2$ coordinate frame. The correction is a negative mass sink term equal to the product of the bottom face area with the withdrawal velocity.
The solidified material in the mould above the strand can move with the withdrawal velocity for those cells with a solidified connection to the strand, as the differentiation between cells in both domains is only a logical one. This is in any case recommended for the continuous casting of steel with a thin and extended solidified skin, but this can cause unrealistic results for other alloys especially when the solidification reaches to the melt free surface at the top of the mould and a downward velocity is prescribed there.

Finally, the heat source term due to advection of the latent heat in the pulled strand is specific for continuous casting and is incorporated in terms of specific latent heat, withdrawal velocity and gradient of the solid fraction [6].

2.4. Melt free surface and inlet flux control in withdrawal
The free surface can be optionally tracked during the whole withdrawal phase, see figure 2(b). Then, the melt level in the mould varies dependent on the process conditions. An increased computational time results due to the adjustment of the CFL-based time step for large velocities in the free-falling stream under the inlet. If small deviations of the melt level from its equilibrium position during withdrawal are not of primary interest, calculation of the melt free surface movement can be omitted immediately or after some transient time as indicated in figure 2(c). This enables achieving the same low computational times as for a prefilled mould. For most industrial applications analysed thus far, the consideration of the dynamics of the melt free surface was not essential.

The filling state of all the regions in the casting setup is analysed automatically before the switch. This is not a trivial task, because the regions may be distributed arbitrarily and furthermore, many various continuous casting setups exist. The applied procedure is to calculate the percent of filled volume for each horizontal grid level individually. The obtained layer wise distribution is analysed for each particular region. One looks for the transition between a value higher than a threshold of 40% not filled and a value smaller than the threshold in the next lower layer starting from the top. The first found position becomes the position of the interface planarization in the considered region.

Finally, the inlet position is transferred downwards to the shifted planarized melt interface. The inlet flux is set balanced with the mass flux of the pulled strand, which is required in order to assure the stationary condition of the melt free surface. There are many other details such as filling of “holes” somewhere in the nozzle in order to assure a realistic configuration with mass flux continuity. The applied method works well in most cases.

2.5. Temperature trace with movable thermocouples
The thermal history at any point attached to the strand material can be traced by thermocouples moving together with it, being stationary in \( S_1 \). Their start position may be defined inside of the prefilled strand or above it. In the latter case, the movable thermocouple will reach the strand after some delay. The host MPI grid partition as well as the grid cell has to be updated for retrieving the thermocouple values for every timestep during strand withdrawal.

2.6. Thermal quality criteria
The continuous casting model considers fluid flow and solidification phenomena simultaneously. The computation of thermal criteria is typically calculated for the solidification only, hence it has to be adjusted for the convective transport due to the strand motion. The computed 3D fields such as solidification time, liquidus to solidus time, thermal gradient, cooling rate, Niyama criteria and microporosity are advected one grid layer downward every time the strand is lengthened by the next grid layer. A special treatment is applied for the cooling rate criterion. The time derivative is composed of the convective component due to the strand motion and the substantive one due to the local temperature change. A 3D criterion “sump depth” shows the distance from the given location in the liquid pool to the strand top.
3. Application examples

The above described models are implemented in the commercial software MAGMA CC. It is a fully integrated solution for the virtual design and optimization of continuous casting processes for aluminium and copper. The software considers the flow, heat transfer, solidification and stress generation in the inflowing metal, the solidifying strand and the mould, and can be used for vertical and horizontal casting processes. As a typical application example for aluminium, the simulation of the start-up phase is shown figure 4. The flow and heat balance in the launder is analysed coupled with the withdrawal process. The start can be controlled by the melt level in the mould or in the launder system. Sometimes the withdrawal starts already before a final meniscus height is reached. Experiments were performed together with the company TRIMET Aluminium SE, Germany on a R&D full-scale casting facility to validate the flow and solidification conditions. Figure 4 shows such a comparison between simulation and the real casting process.

![Figure 4](image)

**Figure 4.** The right hand picture (b) shows an experimental setup of a casting trial using a hot top system for the production of a round shaped aluminium billet (with courtesy of TRIMET Aluminium SE, Essen). Measurements of temperatures with the help of thermocouples were used in this experimental setup to calibrate the simulation and to get the needed heat transfer coefficients. The left hand picture (a) shows the corresponding simulated temperature result.

The simulation allows a combined consideration of forced and natural convection in the liquid metal and in the mushy zone, due to both the inflow and the temperature gradients in the metal. Figure 5 illustrates the application for the two common direct chill casting processes. There is on the one hand the classical process with a floating nozzle and on the other hand the hot top system shown in figure 4 above.

![Figure 5](image)

**Figure 5.** For DC casting of aluminium, the two most common processes are a hot top system or a floating system with a nozzle. The picture (a) shows the temperature distribution for the floating system and the corresponding sump profile. The right picture (b) shows the sump profile in the hot top system.
In figure 6 an application for the vertical continuous casting of a copper alloy is visualized. The cast material is a Cu-Zn alloy. In the case of copper continuous casting, the mould is much longer compared to aluminium processes. The secondary cooling looks also different due to the different spray cooling zones. The results in figure 6 show a comparison between air cooling and water cooling in the secondary cooling. It can be clearly identified that the effect of spray water leads to a faster solidification. But, the effect of the temperature gradient is also a reason for residual stress build up and consequently for crack formation. Especially copper alloys without lead have a tendency for the formation of hot tears. With simulation and a virtual design of experiments, a good strategy for an optimized cooling can be achieved.

![Figure 6](image)

**Figure 6.** On the left side (a) the temperature distribution is shown for a secondary cooling totally without water. This can be necessary especially for alloys with a high tendency to crack. The right picture (b) shows, for the same temperature range between RT and casting temperature, the resulting distribution if water spray cooling is used.

Another example for the use of simulation in continuous casting of copper is shown in figure 7. Here a rectangular shaped format is cast and in the centre a t-shape nozzle is used for pouring. With the obtained results, the sensitivity of a correct position of the nozzle in the mould should be demonstrated. In the left picture the nozzle is not positioned very carefully. This will directly lead to a different velocity field. Inclusions or other flow related defects are the consequence. The optimal design and position of nozzles are a typical application for such a virtual experimentation.
Figure 7. The picture (b) is a process using a t-shape nozzle in a correct way. The nozzle was carefully positioned in the centre, which leads to a velocity distribution to the outsides of the mould. In the picture (a) the nozzle was shifted slightly, which causes turbulence and can be a reason for inclusions and other flow related defects.

4. Summary
This paper describes a modelling approach to simulate the flow and solidification in continuous casting processes. A strong focus is hereby the starting phase. Different possibilities are available. At the end it is always a question of accuracy in competition with computational time. The description of the melt free surface and also the convective flow during solidification has to be considered to get a reliable result.

Furthermore, examples for the application of the models for copper and aluminium continuous casting processes show the benefits for the user. This can at the end help to find robust process conditions to achieve a good product quality. Special thermal and mechanical quality criteria can be used for such virtual experiments.

The next development step for an improved modelling of heat transfer will be to consider an air gap formation between the strand and the mould, including reduced heat transfer due to thermal contraction. For that reason, a full thermomechanical coupling is necessary.

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