Modeling and Removal of Inclusions in Continuous Casting

P. Väyrynen, S. Wang, S. Louhenkilpi and L. Holappa
Laboratory of Metallurgy, Helsinki University of Technology, Espoo, Finland

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Abstract

Continuous casting is the central process phase with strong influence on the final quality of the steel products. Several different models for continuous casting have been developed at the Laboratory of Metallurgy at Helsinki University of Technology (TKK) concerning e.g. fluid flow, heat transfer, thermodynamic equilibria and statistical approaches. In this paper the in-house solidification model called IDS, is presented as well as the fluid flow and inclusion calculations in the tundish and in the mould with the aim to find optimal flow conditions. IDS is a thermodynamic-kinetic-empirical tool for simulation of solidification phenomena and microstructure of steels from melt down to room temperature.

Flow pattern in tundish and in mould is of great interest because it influences many important phenomena that have an effect on the steel quality, especially on inclusions removal. Numerous studies on fluid flow phenomena and inclusions behaviour in tundish and mould have been carried out at TKK for steady state and transient casting conditions. The effect of different kinds of dams in the industrial bloom tundish on the fluid flow and particle removal have been studied and presented in this paper. Similar calculations with and without electromagnetic stirring (EMS) have been carried out for the bloom caster mould. Many different submerged entry nozzle (SEN) designs were used. The results from these mould calculations are also presented.

The examples show that mathematical models can be used in many ways for improved production efficiency and product quality.

Introduction

Continuous casting of steel has become an important route in steel production worldwide, owing to its inherent advantages of energy saving, high yield, flexibility of operation, and competitive casting quality. With the development of the continuous casting technology, emphasis has focused increasingly on the quality improvement and cost reducing aspects of the steel products. One of the most stringent quality requirements today includes the cleanliness of steel. For demanding applications high steel cleanliness and strictly controlled inclusions are required. Inclusions in steel can form either endogenously, i.e. by deoxidation reactions in steel or exogenously, from external sources for example via different reoxidation processes. Primary inclusions are formed during steel treatments in the ladle. Most of these are removed to the ladle slag or on the lining. However, the rest of the inclusions still remain through the successive process stages and additionally new inclusions are formed during casting and solidification.

Cleanliness can be affected strongly by controlling the fluid flow conditions in continuous casting. Direct observation of flow behavior during casting is difficult. For this reason, water models and mathematical models are valuable and widely used in studying the

fluid flow phenomena. Numerous studies on fluid flow phenomena and inclusions removal in tundish and mould have been carried out at Helsinki University of Technology, TKK. They include steady state and transient casting conditions. The main focus of the studies has been on the effects of different kind of tundish flow control devices and submerged entry nozzles (SEN) on flow conditions and inclusion removal, in tundish and mould. Criteria for good flow conditions have also been discussed and studied. The calculations have been carried out for a bloom caster with mould electromagnetic stirring (MEMS) and a slab caster. These studies are presented in this paper.

Thermodynamic calculations can be used to study the formation of different kinds of inclusions. Thermodynamic models are very useful if inclusions should be modified or strictly controlled during casting. For instance, in most industrial practices deoxidation is based on aluminium. Aluminium deoxidation results in formation of Al_2O_3 inclusions which mostly are removed from the steel melt but as a certain minor population remain in the final steel melt. These inclusions are hard and non-deformable and they tend to form oxide clusters. Therefore they can disturb casting by clogging nozzles and in solid steel be harmful in certain products. For instance in thin wires and wire springs alumina inclusions are quite detrimental. Silicate type inclusions which are deformable in hot rolling conditions are preferred in such products. At TKK thermodynamic-kinetic tools (IDS and ICA) are developed to calculate solidification phenomena including inclusions during casting. These tools are also presented in this paper as well as some calculation examples.

Thermodynamic Modeling of Inclusions

There are in general two common methods available for modeling of inclusions and precipitations. They are the Gibbs free energy method and the solubility product method. The solubility product concept can only be used for specific, mainly for binary inclusions or precipitations. It is based on the experimental solubility products measurements. In general more data about solubility products of inclusions and precipitates in different phases are still needed. The other concept, Gibbs free energy, is more general. It is based on the minimization of the Gibbs free energy of the whole system (bulk phase + inclusions). Inclusions or precipitates are formed if they reduce the free Gibbs energy of the whole system. In this way also more complex inclusions or precipitations can be calculated. For calculations a Gibbs energy calculation algorithm and corresponding thermodynamic databank are needed. The tools, IDS and ICA, are based on the free Gibbs energy method. These tools are presented in the following chapters.

IDS-Package

At TKK the solidification and microstructure tool called IDS has been developed since 1984 [1, 2]. The tool calculates the solidification and cooling related phenomena including the solid state phase transformations from liquid state down to room temperature. IDS is based on the thermodynamic and kinetic theories of solidification and cooling. It also utilizes assessed thermodynamic data as well as regression formulas of experimental data. IDS includes two main modules, the IDS module and the ADC module. Both modules have their own recommended composition ranges. In addition IDS tool calculates important thermophysical material properties (enthalpy, specific heat, thermal conductivity, density and thermal contraction) from liquid state

down to room temperature as well as the austenite grain size, the liquid viscosity and the surface tension.

The present version of the IDS module is valid for simulation of the solidification of low-alloyed steels and stainless steels (Cr up to 24 wt% and Ni up to 16 wt%). The model applies a thermodynamic substitutional solution model, magnetic ordering model and Fick's diffusion laws to determine the stable solution phases, liquid L, delta ferrite δ, eutectic ferrite for stainless steels and austenite γ and their fractions and compositions as a function of temperature. These calculations take into account the effect of solutes C, Si, Mn, P, S, Cr, Mo, Ni, Cu, Al, N, Nb, Ti, V, Ca, B, O and H, cooling rate and dendrite arm diameter. Also the formation of some binary compounds (MnS, NbC, NbN, TiC, TiN, VC, VN, AlN, BN, CO, SiO_2, Al_2O_3, CaO, CaS, Ti_3O_5, Ti_2O_3, TiO_2) are simulated based on the Gibbs energy concept. At the phase interface, the IDS module solves the thermodynamic equilibria of two solution phases, δ and L, γ and L, and γ and δ, using the chemical potential-equality equations for each component (i = 1,..,n) of the alloy (Equation 1):

$$\mu_i^{\phi 1}(T, x_1^{\phi 1},.., x_n^{\phi 1}) = \mu_i^{\phi 2}(T, x_1^{\phi 2},.., x_n^{\phi 2}) \quad (1)$$

In the equation, μ_i^{ϕ} is the chemical potential of the component i in phase ϕ, x_i^{ϕ} is the mole fraction of the component in phase ϕ, T is temperature and n is the number of components in the alloy.

ADC module is a semi-empirical solid-state phase transformation model for steel. It simulates the austenite decomposition process. In the case of low-alloyed steels, the simulation involves the formation of pro-eutectoid ferrite, pro-eutectoid cementite, pearlite, bainite and martensite, and in the case of stainless steels, the formation of martensite only. The ADC model applies a thermodynamic substitutional solution and magnetic ordering model, a carbon diffusion model and special regression formulas based on the CCT experiments. The simulation takes into account the effect of solutes C, Si, Mn, Cr, Mo and Ni, cooling rate and austenite grain size. The ADC model also calculates temperatures Ae_3 and A_{cm} taking into account the effect of the 18 solutes of IDS simulation mentioned above.

The IDS package has been validated by comparing the calculations with experimental data. The comparison has been made for important solidification-related temperatures (liquidus, austenite formation, zero-strength and solidus temperatures), solute microsegregations and solute partitions between different phases. In the case of stainless steels, also the solidification modes and the residual ferrite contents were considered. Good agreement was obtained between the calculations and the experimental data. Model is widely used in research organizations and in companies all around the world. The new version of the IDS is under work. Figure 1a shows the input data which IDS tool demands, following by the output data what IDS calculations offer. Figure 1b illustrates the user interface of IDS tool.
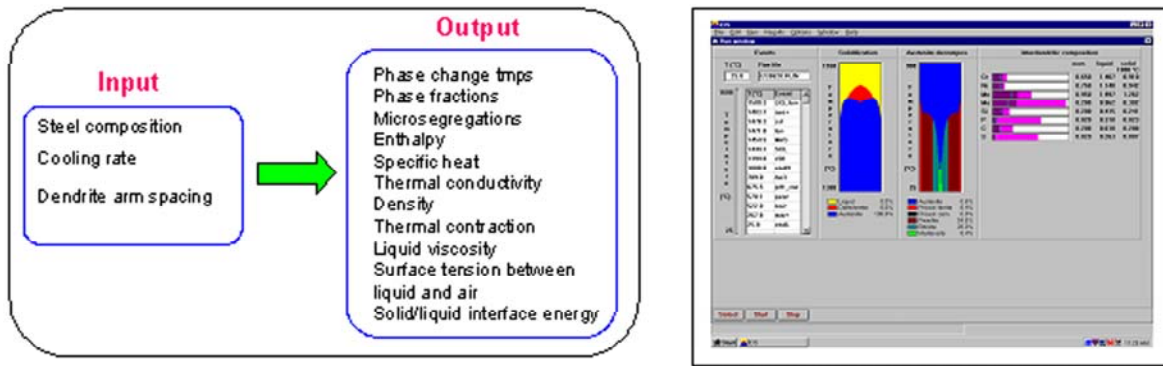
Figure 1 a) Input and output data of IDS, b) User interface of IDS tool.

ICA-Tool

IDS tool calculates only specific, binary inclusions presented above. For the calculation of more complex, multiphase inclusions, the IDS tool is coupled with the ChemApp tool. ChemApp is a thermodynamic programmer's library developed by a German company, GTT-Technologies. This coupled package called ICA [3] offers great potential for both kinetic and thermodynamic modeling of steel solidification and inclusion formation/transformation in the residual liquid fraction. The coupling is iterative so that IDS package simulates at each temperature step the solidification phenomena and the solute distribution (microsegregation) during the solidification and then ChemApp software is used to calculate the formation of multiphase inclusions from the enriched melt. During solidification, the inclusions can be removed from the liquid to the solid as the steel is solidifying. Also the content of the element in the melt is reduced in the same ratio as the element is forming inclusions. Both tools have their own thermodynamic databanks. The ICA tool will be extended to simulate also the solid state precipitations after solidification. This work is under progress. Figure 2 shows the principle of the coupling concept.
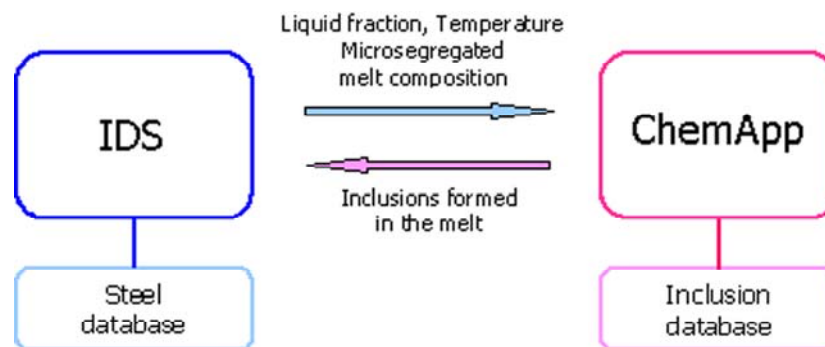

Figure 2 Principle of the coupling concept between IDS and ChemApp.

Case-example: Simulation of Inclusions from Ladle Treatment to Solidification Using ICA-tool.

Inclusion formation in high carbon and silicon spring steels was investigated during ladle treatment and casting by thermodynamic evaluations and experimental heats at Ovako Wire, Koverhar Steelworks [4]. The composition of the steel was 0.725 % C, 0.23% Si, 0.56% Mn, 0.0021% Al, 0.0019% Ca, 0.0037% O. Theoretical calculations were performed with previously mentioned ICA model (ICA = IDS + ChemApp). The basic idea was to intensify silicon deoxidation by bringing the steel in intimate contact with slag which had a proper composition. Thermodynamic calculations and simulations of inclusion formation and transformation during casting and solidification showed that it is possible to produce steel without aluminium deoxidation and to get a product with: low total oxygen content (around 20 ppm), low aluminium content (below 0.002%), good oxide cleanliness without hard alumina inclusions and clusters and soft deformable Ca-Al-silicate inclusions. Results from experimental heats were in good agreement with the theoretical calculations with ICA model. The formation of different inclusions during solidification is summarized in Figure 3.
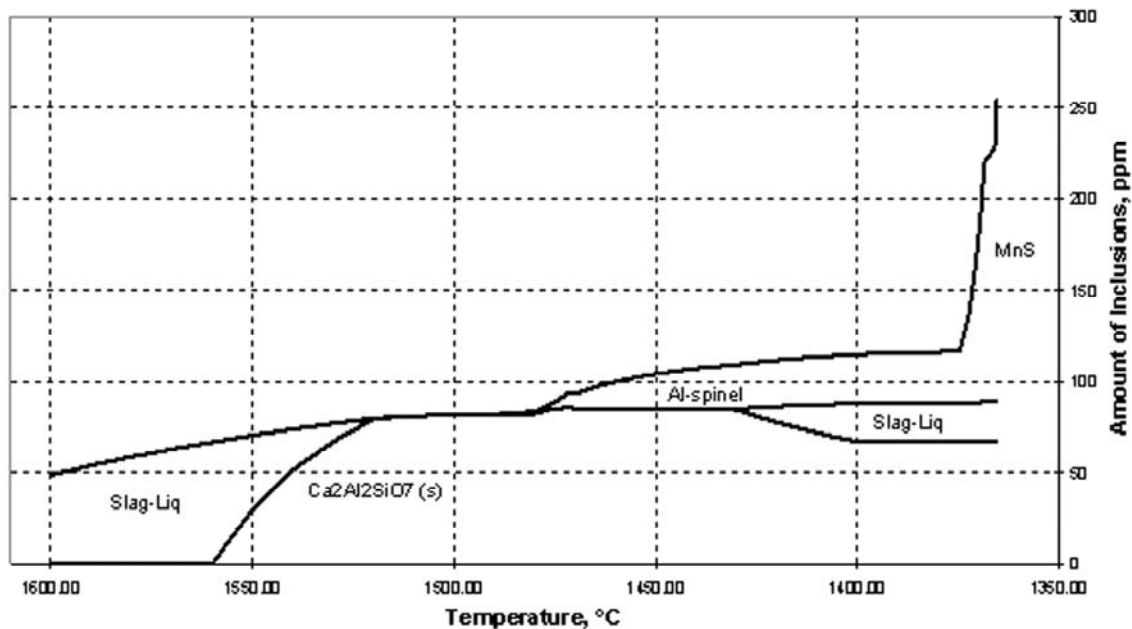

Figure 3 Amount of different inclusions in steel during casting and solidification progress.

Modeling of Inclusion Removal in Tundish and Mould

Mathematical models of fluid flow can be applied to many different aspects for ladle, tundish and mould. Numerous studies on fluid flow phenomena and inclusions behaviour in tundish and mold have been carried out at TKK for steady state and transient casting conditions. Different turbulence models and other important model variables have been studied and tested. Calculations were carried out using commercial CFD tools (FLOW3D, FLUENT and FIDAP).

Even if the slag layer is playing important role in inclusion entrapment and extensive research is being made on these fields, main focus of inclusion removal in tundish and in mould

is on fluid flow. Melt flow can be characterized by solving the standard fluid flow, heat transfer and associated turbulence equations. Depending on the problem, either time-dependent or steady-state equations will be solved. For example, during normal casting operation, it may be sufficient to solve the steady-state form of these equations. On the other hand, during the ladle change operation, the time-dependent equations need to be solved. Since flow in a tundish is not necessarily laminar, it becomes mandatory to incorporate equations for a turbulence model, e.g. the commonly used κ-ε model. Thus, for a three dimensional, turbulent, steady-state flow problem in which heat transfer aspects are considered, the steady-state form of the equations of continuity, momentum, turbulent kinetic energy and heat transfer are being solved. In the next chapters, case examples for the bloom casting tundish and the mould are presented. The aim has been to find solutions to improve the steel cleanliness. The tundish calculations were made by FLOW3D software and the mould calculations by FLUENT. The particle trajectories are calculated using the Langrangian particle tracking method, which solves a transport equation for each particle as it travels through a previously-calculated velocity field.

Effect of Flow Modifiers in the Bloom Tundish

In this study inclusion calculations for tundish were performed only during steady state situation and simultaneously with flow calculation. In the beginning of the particle simulations 10 000 particles were inserted to inlet flow and the number of particles going through outlets was monitored. Boundary condition for particles was set so that they would bounce back to the melt from the walls as well as when they are come in contact with the free surface. All particles had the same density (3000 kg/m^3), but their diameters varied from 15 to 215 μm. Simulations were done in both isothermal and thermal conditions, to quantify the effect of buoyancy in the case.

Used tundish has simple rectangular shape and it provides steel for two moulds. Because of small tundish size, possibilities for flow modifiers are relatively limited (Figure 4).
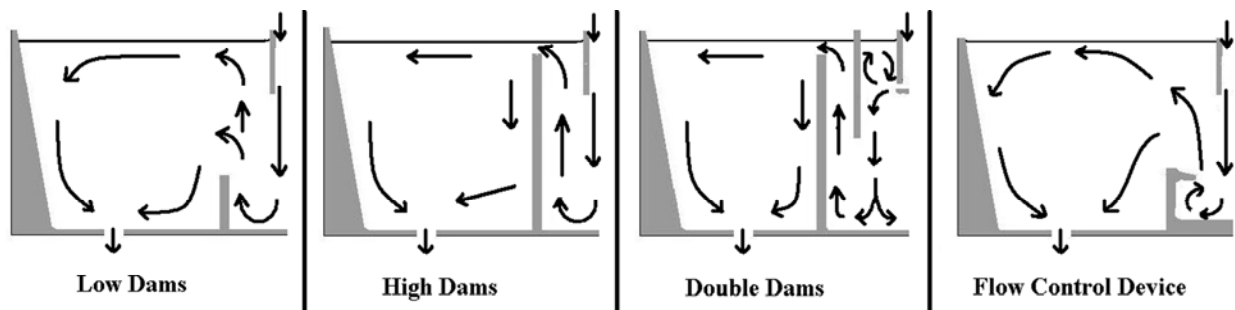

Figure 4 Schematic presentations of the simulated flow modifier configurations (view from the side of the tundish, only one half of the tundish visible)

All configuration options changed flow greatly in the tundish. In the first option with higher dams, interesting observation was the effect of emptying holes. Even though main flow pattern was towards the surface, high velocity flow through the emptying holes was clearly present. During the simulation this flow did not stay steady, but it could change dramatically even during short periods of time. Further studies showed that placement of the emptying holes have effect in this kind of flow behaviour.

Double dams and flow control device options both worked in similar way, even though they differ in design. With double dams changes in the nozzle design direct the incoming flow

straight to top weirs, which slows down the flow velocity. Velocities are slowed even more with the aid of high dams. Single flow control device placed directly under the regular straight ladle nozzle seemed to work similarly. If the incoming flow hit nicely in the flow control device, flow velocity was decreased significantly and flow was also directed towards the surface. All of which are good for particle separation.

Results of the isothermal simulations showed all of the new tundish geometry options to be significantly better than low dams which were used as reference results (Figure 5). By looking only the amount of outgoing particles, it is quite difficult to choose the best option since the good alternatives are very close to each other.
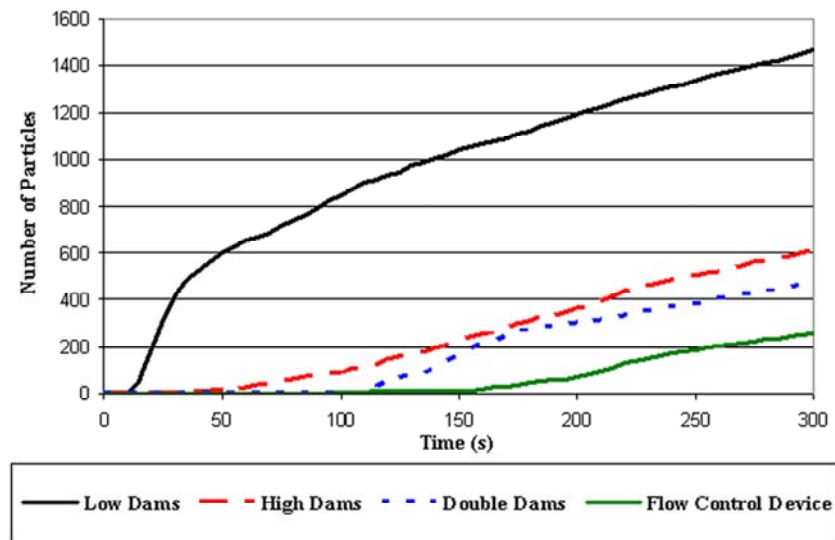

Figure 5 Number of particles leaving the tundish with different tundish configurations (isothermal simulations)

Isothermal modeling is common in physical modeling, where heating of the fluid can be difficult. However, it is known that natural convection significantly alters the flow fields even in a water model and so isothermal experiments of tundish fluid flow should be considered inaccurate [5]. It has to be also noted that with non-isothermal water model the density difference between temperatures are quite different from steel in actual tundish. In order to obtain similar buoyancy force according to Boussinesq approximation water temperature difference is required to be more than 30°C.

In order to find out real effect of the temperature difference, new flow modifier configurations were also simulated with heat transfer model (Figure 6). In these simulations heat transfer was modelled by using fixed heat flux for tundish bottom, walls and steel/slag interface [6] and natural convection was introduced with the use of the Boussinesq approximation.
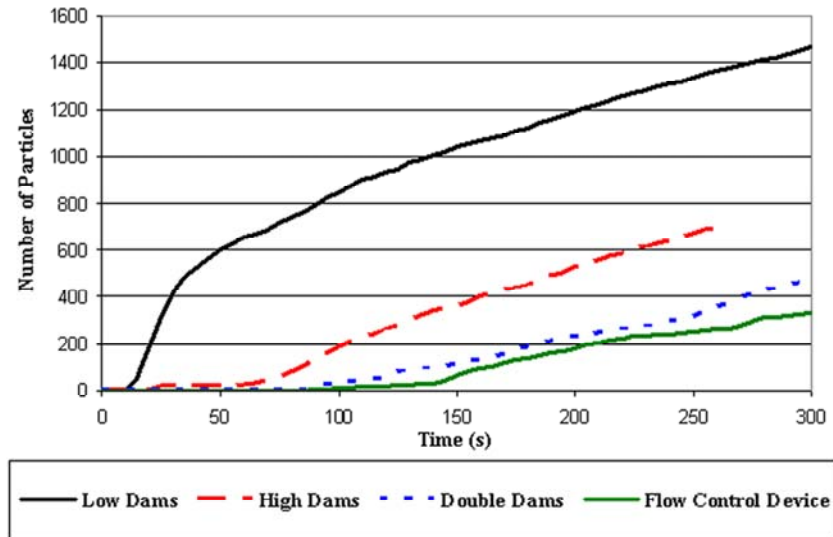
Figure 6 Number of particles leaving from the tundish with different tundish configurations (thermal simulations)

Thermal conditions made difference of the new configurations smaller. When comparing the results (Figures 5 and 6) it can be seen that performance of the high dam configuration is getting better. Changes in physical condition do not seem to affect much to the results of the double dam and single flow control device configurations.

Beyond the numbers there lies interesting information on inclusion removal. When looking outgoing inclusions sorted by their diameter, difference between different options is clearer. All simulations showed that if inclusion diameter is large enough, inclusions will not usually cause any problem. Most of the inclusions that moved out of the tundish had diameter smaller than 90 microns. Difference between high dams and double dams with the new ladle nozzle is that in practice all large inclusions were trapped in the tundish with double dams. With high dams some of the larger ones were also moving out, even though total amount was quite small. Difference with double dams and flow control device was that with the latter fully trapped inclusion size decreased even more. When all inclusions larger than 90 μm were trapped in tundish with double dams, with flow control device the threshold size was 65 μm, respectively.

Based on the results, the single flow control device was found to be the best option.

Modeling of Inclusion Removal in the Bloom Mould

Flow in the mould is of great interest because it influences many important phenomena that have far-reaching consequences on strand quality. TKK has made a lot of calculations for a bloom caster with MEMS in the mould. The objective was to produce cleaner steel and find out the optimal solutions for MEMS parameters as well as to other casting parameters including the nozzle design. The following phenomena were studied: liquid metal flow in the mould, the shape of the free surface, inclusion paths and removal. Five nozzle designs and two casting speeds (0.355 and 0.6 *m/min*) were studied (Table 1).

Table 1 Simulated nozzle designs

	Number of Ports	Port Angle (degrees)
Nozzle #1	2	-30
Nozzle #2	2	-15
Nozzle #3	1 (straight nozzle)	
Nozzle #4	2	+15
Nozzle #5	4	+15

It was found that the electromagnetic stirring dominates the flow field in the bloom mould and the nozzle design influences only little on the velocity distribution, particle separation and the meniscus shape. As to the inclusion separation, however, the straight nozzle seems to be slightly worse than the other nozzles studied. In general, however, with EMS on, small particles separated better compared with the cases when EMS was not in use, whereas any similar effect could not be observed in the case of larger particles. The casting speed has a clear influence on the separation of the inclusions in the continuous casting bloom mould. This all means that the nozzle design or EMS parameters do not affect so much on the cleanliness as the casting speed. So, the easiest way to produce cleaner steel seems to be just to reduce the casting speed. The Lorentz force was calculated using an analytical equation. In the equation, a constant f is given and it describes the stirring intensity. Some discussed results are presented in Figures 7 and 8.
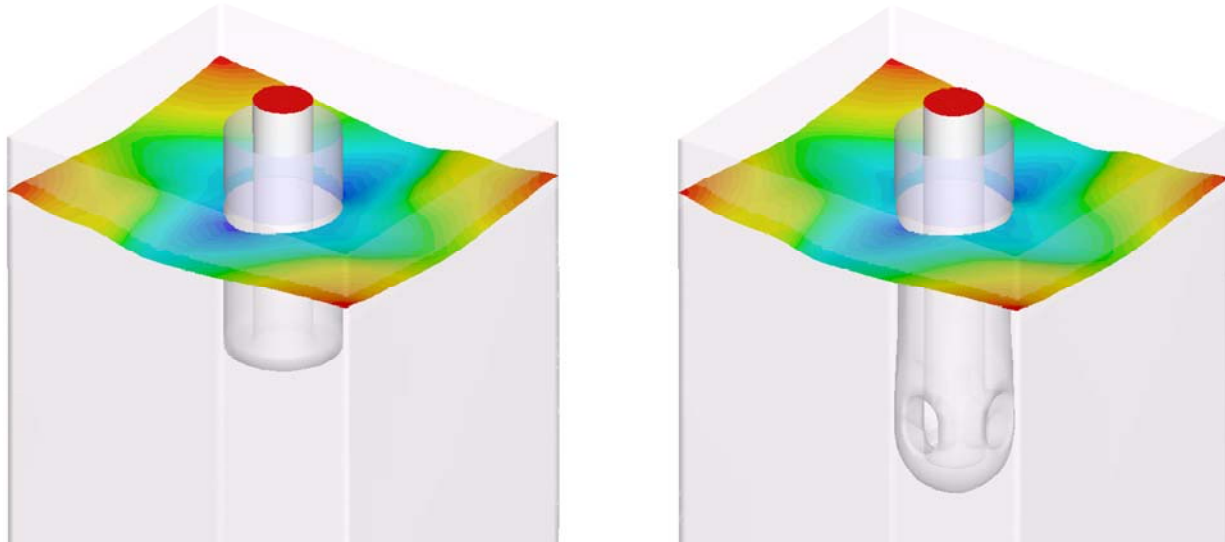
Figure 7 Electromagnetic stirring dominates the flow in the mould. For instance the shape of the meniscus is almost the same for nozzles #3 (straight) and #5 (four holes). Casting speed 0.6 m/min, f was 0.5 and frequency 2.0.
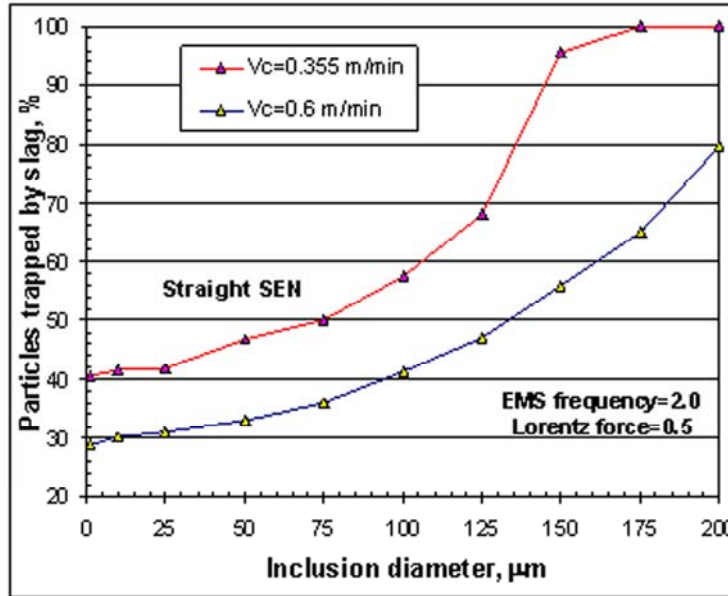
Figure 8 Casting speed has a clear influence on the separation of the inclusions in the continuous casting bloom mould.

Criteria for Good Flow

Tundish Flow

The Weber number is a dimensionless number in fluid mechanics that is often useful in analyzing fluid flows where there is an interface between two different fluids, especially for multiphase flows. It can be thought as a measure of the relative importance of the fluid's inertia compared to its surface tension.

Emulsification of ladle slag into steel during stirring is a phenomenon which has been studied by several researchers using physical and mathematical modeling. Slag emulsification has been thought possible to happen except in ladles also in tundishes and in moulds during casting. The modified Weber number (Equation 2) is a derivation of the original Weber number which applies more precisely to steel/slag-problem [7]:

$$We = \frac{\rho_m v_m^2}{\left(\sigma g(\rho_m - \rho_s)\right)^{1/2}} \geq 12.3 \quad (2)$$

In Equation 2 v_m is radial metal velocity, g is gravity, σ is interfacial tension and ρ_m and ρ_s densities of metal and slag. When modified Weber-number is 12.3 or over a strong tendency for dispersion of the slag layer into the bulk steel can be assumed. According to the calculations, this is not a problem in normal steady state conditions, since velocities are too low. However if fluid level is lower and bulk steel velocity is higher, e.g. during ladle/grade change, critical Weber number value can be exceeded in some areas of the tundish [8].
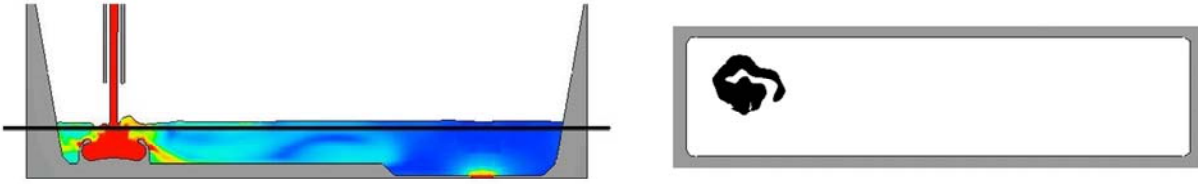
Figure 9 Tundish fluid flow soon after the new ladle opening is presented on the left. Line across the figure shows where the figure on the right has been taken from. Dark areas on the right side figure present areas where modified Weber number is over 12.3.

Mould Flow: Slab Caster Example

The main purpose of CFD modeling at Laboratory of Metallurgy at TKK is not just to find solutions to individual cases but also to use these individual cases to define general criteria for how to quantify good flow pattern. Numerical values are defined based on flow simulations and their value must fall inside given safety variability ranges. The values have been estimated by simulating process conditions leading to acceptable steel quality. By making several calculations with "good quality" conditions, safety ranges for chosen criteria can be defined. This concept was firstly tested in Outokumpu Tornio Works, Finland [9]. About 50 different calculations were carried out with different SEN designs and casting parameters and the best one combination was tested in the caster with excellent results. The calculations were carried out with FIDAP software. The following criteria and safety ranges were used:

Top surface velocity	$0.2 - 0.3\ m/s$
Top surface kinetic energy	$0.025 - 0.04\ m^2/s^2$
Surface wave height	$10 - 20\ mm$
Penetration depth	$2 - 4\ m$
Impinging velocity to narrow face	$0 - 0.25\ m/s$

Summary

Laboratory of Metallurgy at TKK has involved in developing process and other models now for over two decades and has succeeded in creating models that have been widely accepted in academia and in industry to daily use. In this paper in-house thermodynamic models are applied in inclusion engineering and commercial CFD tools in optimization of flow pattern in tundish and mould. It shows that mathematical models can have many uses in optimizing and development of steel production during continuous casting.

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