Control of Fluid Flow, Heat Transfer and Inclusions in Continuous Casting: CFD and Neural Network Studies

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Abstract

Fluid flow and heat transfer calculations have been carried out in tundish and mould including different kind of submerged entry nozzles. The effect of different kind of tundish dams have been studied in a bloom tundish in steady state and transient conditions. Many different CFD parameters, like turbulence models and mesh density, were tested during the studies. CFD calculations were also carried out to study the effects of swirling flow inside the SEN as well as different kind of SEN nozzles on mould flow phenomena. Different kinds of criteria for the ideal mould flow were derived. Neural network model was developed to predict and control the tundish temperature from process parameters and casting time. The model, which is based on the Bayesian MLP neural network, includes 13 inputs from ladle cycle and the output is the tundish temperature. The results were good; the mean error for temperature was 3.4 °C.

Introduction

Secondary steelmaking and continuous casting are the central process phases with strong influence on the final quality of the steel products. Liquid steel processing in ladle, tundish and mould consist of a complicated series of complex chemical, physical and thermal phenomena. Strict control and smooth operation are extremely important but quite challenging tasks due to scarcity of direct measurements which would describe dynamic changes in steel chemistry, temperature, flow conditions and interactions with e.g. covering slag, refractory materials or mould wall. Modelling of reactions, flow dynamics and heat transfer can give a better understanding of different phenomena and their relations to different process parameters as well as it can advice to optimized process run.

The metallurgical industry carries out a lot of experimental research, industrial trials, and collects gigabytes of process data nowadays. Making the trials and measurements is often very difficult, resource and time consuming because the processes are very complicated, closed and temperatures are usually very high. It is also a challenge to find ways to actually use available data to optimize the process or to develop a deeper understanding of governing phenomena. Mathematical modelling offers one solution to this challenge. During the last twenty years, a lot of mathematical models have been developed for metallurgical processes and they are today increasingly applied in the industry. However, for many processes it is still very difficult or impossible to find a comprehensive model and such models are still needed. The development of these models requires a very good understanding of the process. Sometimes, due to complexity of the processes, statistical methods e.g. neural networks are used for modelling, especially when a lot of process data is available.

In the Laboratory of Metallurgy at Helsinki University of Technology (TKK), Finland, a lot of CFD calculations have been carried out for tundish and mould. The main purpose of CFD modelling at Laboratory of Metallurgy 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. In the laboratory, also many statistical models for continuous casting have been developed. Different kind of advanced statistical methods were applied, like the standard MLP (Multi-Layer Perceptron) neural network but also the Bayesian MLP neural network.

In this paper, the main results of the CFD calculations for continuous casting are presented as well as the neural network model for predicting and controlling the tundish temperature using process parameters and casting time. The examples show that, mathematical models can be used in many ways for improved production efficiency and product quality.

Fluid flow calculations in tundish and mould

To study the fluid flow phenomena in tundish or mould is problematic. To make direct observations and empirical investigations during casting are very difficult and expensive. Usually direct methods are replaced by using physical modelling with water, mathematical modelling or combinations of both. Physical modelling gives significant insights into the flow behaviour but due to the complexity of the physical phenomena like natural convection due to temperature gradients, exact knowledge of e.g. inclusion separation is difficult to obtain. In recent years, mathematical simulation has become more and more popular because of developments both in computer hardware and software. However, to use a mathematical model many issues like used mesh density and turbulence model must be studied, proper selections and validations to be made before the results of the mathematical simulations are reliable enough. Generally, however, mathematical modelling has the advantage of easy extension to other phenomena such as heat transfer, particle motion and two-phase flow, which is difficult with isothermal water models. 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. 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).

<u>CFD calculations in tundish</u>

Firstly, calculations were carried out to test and validate the mathematical model. After that the effect of different kind of dams on flow conditions and inclusion separation were studied in a bloom tundish. The following steps were carried out to validate the model:

- Study the mesh density
- Study the effect of different turbulence models
- Validate the results with industrial trials
- Validate the results with water model

<u>Validation Using Steel Plant Experiments</u>

Best way to monitor performance of different tundish configurations in the steel plant is to monitor elemental concentrations during the steel grade change. Measurements were taken from the mould and started immediately when ladle of new steel grade was opened. In the first phase of the casting samples were taken every 0.5 meters of cast steel and later on every 1 meter and every 2 meters. During every grade change at least 10 samples were taken. The element to monitor differs depending on what kind of steel grades are cast. In this project it was found to be best to monitor carbon content, since the change in carbon content between cast grades was clear enough. The elemental analysis was carried out during the first 29 tons cast steel (Fig. 1). Since all the simulation results from full scaled industrial model are accurate when compared to available experimental data, the commercial CFD model is relatively well validated [1].

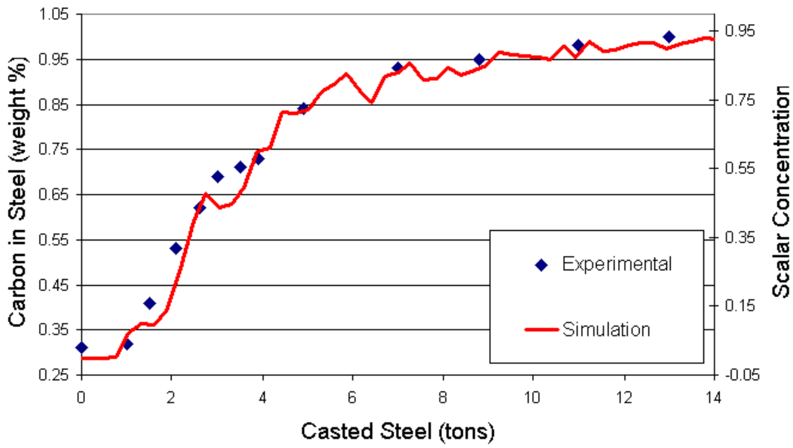

Figure 1 : Measured and calculated carbon content during steel grade change in a tundish

Validation Using Water Model Experiments

Validation with water model was made by comparing the C-curve results of the experiments and scalar concentration curves from the simulations [2]. Water model experiments were carried out in Foseco Steel, Borken, Germany. In this study red colour liquid dye having similar density as that of water was used as a tracer for C- curve studies. C-curve is obtained by injecting a known amount of dye into the model ladle shroud and monitoring the transmittance of light through the exit stream by a colorimeter. The tundish model was constructed using a 1/3 scale factor and based on Froude similarity. Simulation results still showed higher concentration peak in the beginning, which would indicate that flows are still faster than in the experiments [1].

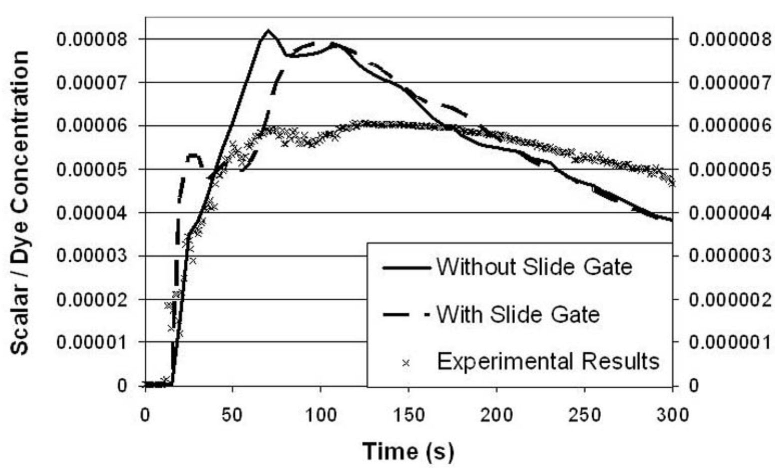

Figure 2 : Comparison of the C-curve results of tundish with no flow modifiers with and without slide gate system

Difference between experimental and simulation results was clear (Fig. 2). Simulation results still showed higher concentration peak in the beginning. Simulation with accurate design of slide gate produced only slightly different results. Minimum residence time is same, but first concentration peak does not rise as high as in the case without the slide gate. The probable causes for different C-curves are believed to be the experimental dye concentration measurement method, which is not accurate enough. But hence the industrial trials gave very good results, it was believed that the mathematical model was well validated.

Particle Calculations in the Bloom Tundish

In this part of the study inclusion calculations were performed during steady state situation and simultaneously with flow calculation. In the simulations 10 000 particles were inserted to inlet flow and the number of particles going through outlets was monitored. From the walls particles were set to bounce back to the melt as well as when they came to in contact with the free surface. All particles had same density (3000 kg/m^3), but their diameters varied from 15 to 215 µm. In particle calculations used tundish also had rectangular shape but it provides steel for two moulds. Because of the small tundish size, possibilities for new flow modifiers were relatively limited. Used practice included two low dams (Dam #1). Since principal idea behind tundish dams is to direct flow closer to the surface, idea of using higher dams was first new alternative (Dam #2). Higher dams were equipped with emptying holes around the same height as top of the originally used dams to limit amount of scrapped metal at the end of the each casting sequence. Second modifier option was more complex dam variation (Dam #3). Variation included similar high dams as first option, but they were placed further away from the ladle nozzle. Ladle nozzle was changed from regular straight flow nozzle to nozzle which directs flow in 90 degree angle to both sides. Top weirs were also introduced to block fast nozzle flow from new nozzle design. Last option was tundish without any dams, only with rectangular turbulence inhibitor below straight ladle nozzle (Dam #4). All options changed flow greatly in tundish. Simulation results showed all of the new tundish geometry options to be significantly better than low dams (Fig. 3). Best performance was observed with uniquely designed turbulence inhibitor [3].

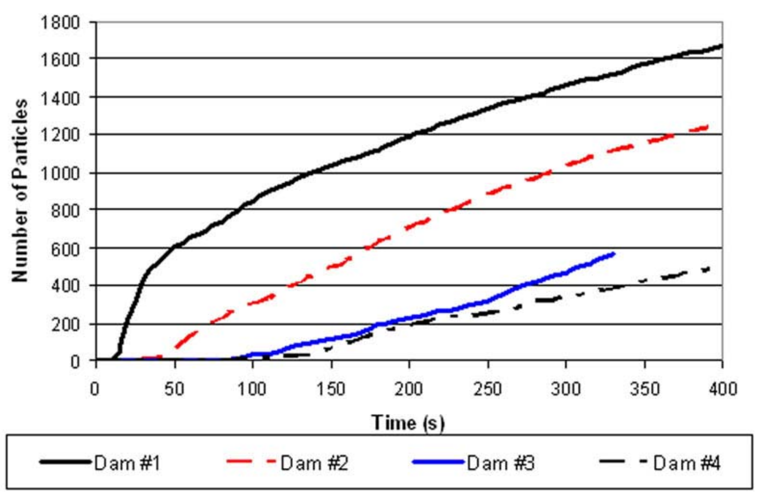

Figure 3 : Number of particles left from the tundish with different flow modifiers

CFD calculations in mould

CFD mould simulations have been carried with a bloom mould with mould electromagnetic stirring (MEMS) [4]. Coupled simulations are carried out to calculate turbulent fluid flow in the mould, meniscus 3D-shape (free surface), and inclusion paths using different stirring parameters, inclusion sizes, five different SEN-nozzle designs and two casting speeds (v=0.355 m/min and v=0.6 m/min). The five nozzles were:

Nozzle 1: two holes, port angle -30 degrees down
Nozzle 2: two holes, port angle -15 degrees down
Nozzle 3: straight
Nozzle 4: two holes, port angle +15 degrees up
Nozzle 5: four holes, port angle +15 degrees up

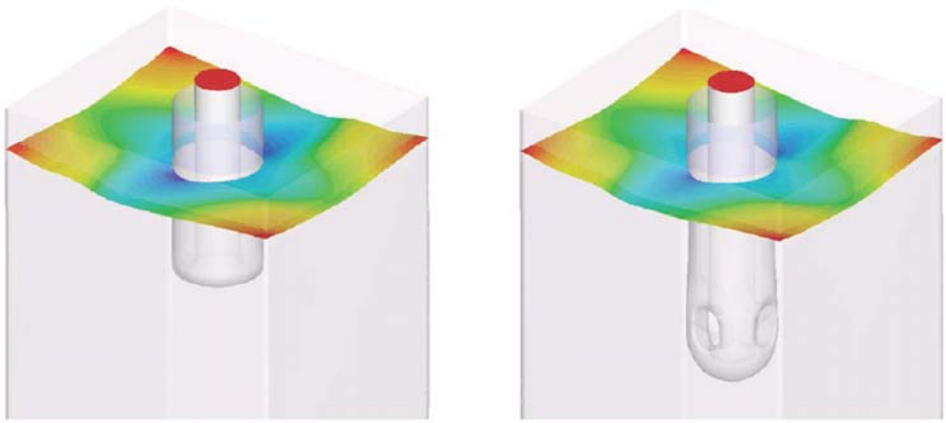

Figure 4 : Electromagnetic stirring dominates the flow in the mould. For instance the shape of the meniscus is almost the same for nozzles No. 3 (straight) and No. 5 (four holes). Casting speed 0.6 m/min.

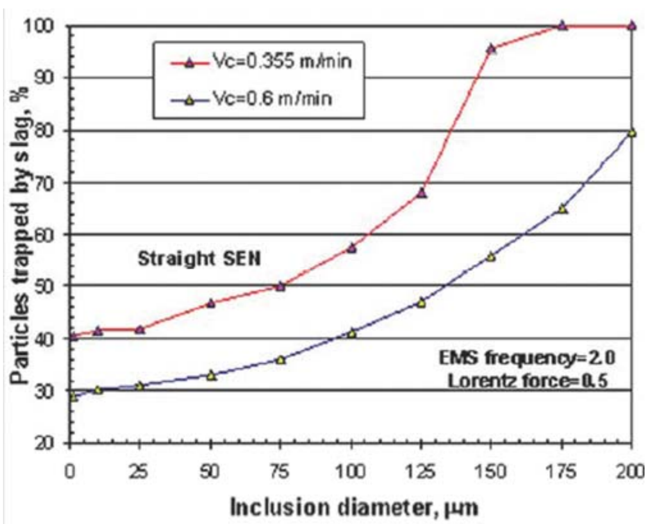

Figure 5 : The casting speed has a clear influence on the separation of the inclusions in the CC bloom mould.

In general, the effect of stirring on the flow phenomena and meniscus shape (Fig. 4) was very strong and EMS dominates the flow in the mould. With using EMS small particles separated better compared with the cases when EMS was not in use, but larger particles not. It can also be seen, that the nozzle design had not so big influence on the inclusion separation. However, the straight nozzle seems to be the worst one and the two and four holes nozzles all are slightly better. The effect of the casting speed on the inclusion separation is very clear (Fig. 5). With smaller casting speed the separation is much better compared with the higher casting speed. This all means that the nozzle design or EMS parameters do not affect so much on the cleanliness than the casting speed.

Ideal mould flow conditions

The general question is, how to define general criteria for good flow pattern. At TKK, numerical values are defined based on flow simulations and their value must fall inside given safety variability ranges. The criteria concept was preliminary tested in Outokumpu Tornio Works, Finland. About 50 different calculations were carried out with different SEN design and casting parameters and the best one was tested in the caster with excellent results. 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

Swirling flow inside SEN

TKK has made also numerical simulations to study the effects of swirling flow in the submerged entry nozzle (SEN) on the flow and inclusion removal [4]. Swirling flow is generated by electromagnetic stirring (SEN-EMS). Calculations are carried out for a bloom caster. Calculations included turbulent fluid flow in the SEN and mould, meniscus 3D-shape (free surface), and inclusion paths. Different stirring parameters for SEN-EMS as well as for mould EMS (MEMS) were used.

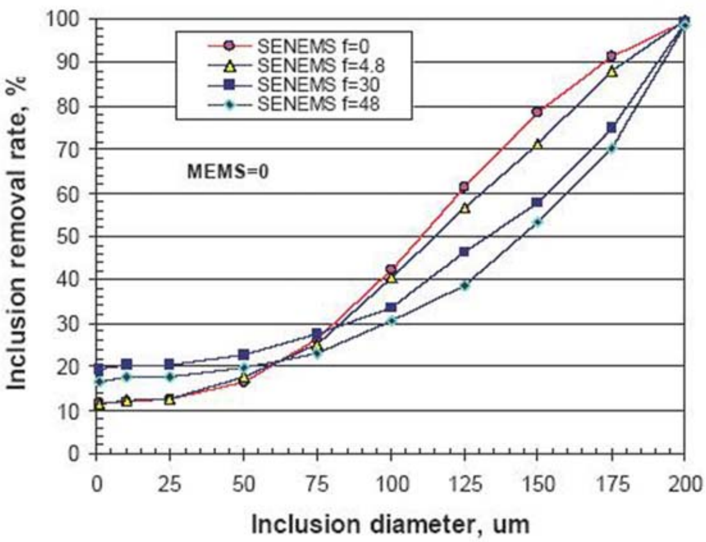

Figure 6 : Effect of SEN-EMS alone on the inclusion removal in the mould; bloom caster; f is the relative intensity.

The main conclusions are that a) SEN-EMS alone does not work sufficiently for inclusion removal (Fig. 6), b) together with MEMS, SEN-EMS improves cleanliness by about 10 % compared to MEMS only c) SEN-EMS with or without MEMS does not affect meniscus surface velocities very much but MEMS affects a lot.

Tundish temperature prediction using neural network

At TKK, many statistical models have been developed. They are for instance:

- Models for steel hardenability (Jominy curves)
- Models for tundish temperature
- Models for as-cast slab width
- Prediction of sticker defects

A statistical model for prediction of tundish temperature has been developed. It is important to accurately control the tundish temperature in steel plant and for that purpose a good model is needed. The model can also be connected to CFD calculations to estimate the steel inlet temperature for transient tundish calculations [5]. The model developed is based on the Bayesian MLP neural network. The process data were obtained from Ruukki Raahe, Finland (data from 367 heats including the continuous steel temperature measurements from tundish). The model includes 13 inputs from ladle cycle and the output is the tundish temperature (Fig. 7). The results were good, the mean error for temperature was 3.4 °C and R2 was 0.85 (Fig. 8). An easy-to-use Excel-based simulator tool has been developed for the examination of the modelling results. The simulator tool can be used for testing the model with new data, examination of the influences of different variables to tundish temperatures and drawing diagrams from the results of simulation

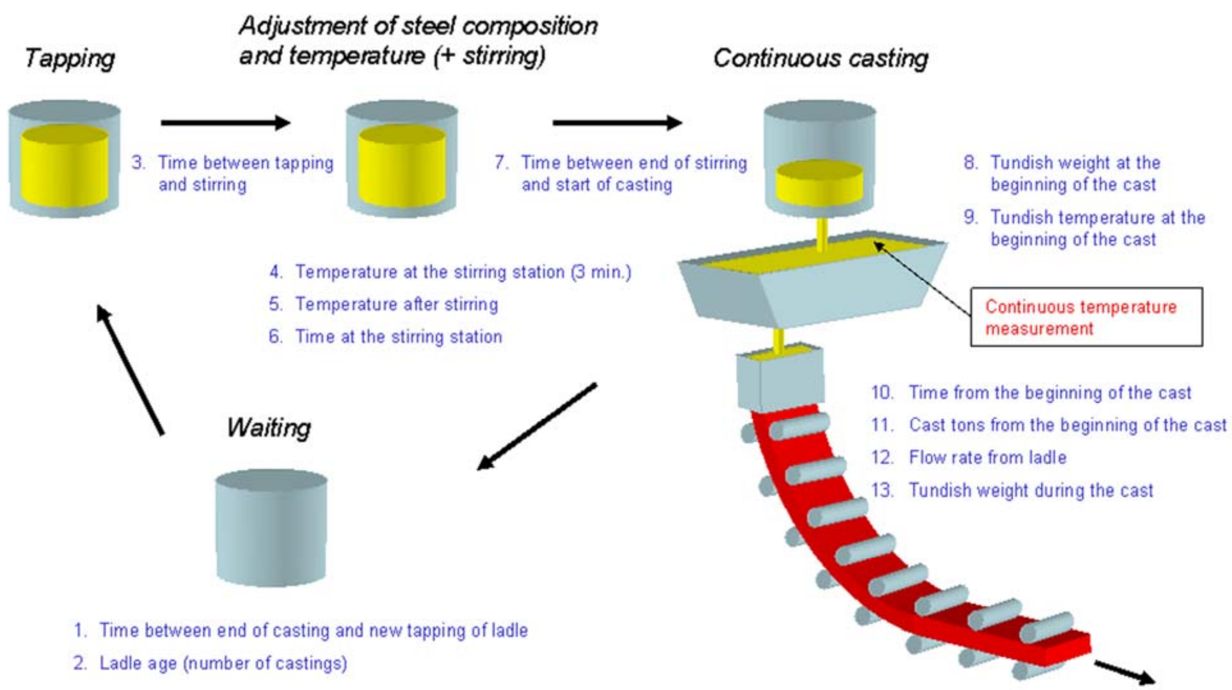

Figure 7 : Neural network inputs from the ladle cycle

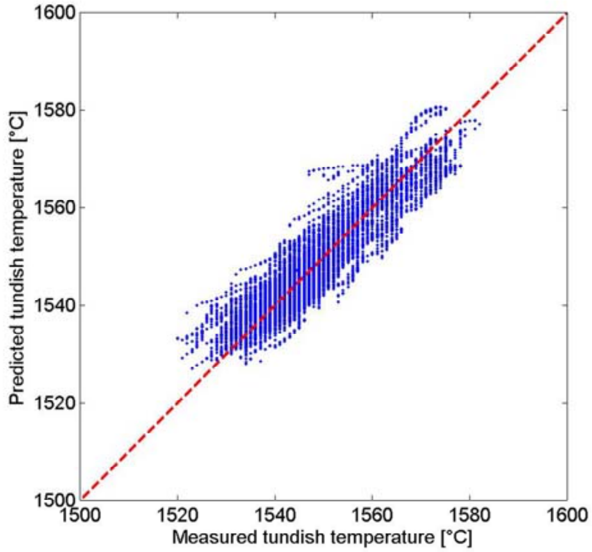

Figure 8 : One example of the simulated and measured results for tundish temperature.

Conclusions

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, the main results of the CFD calculations for continuous casting are presented as well as the neural network model for predicting and controlling the tundish temperature using process parameters and casting time. The examples show that, mathematical models can be used in many ways for improved production efficiency and product quality.

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