A COMPREHENSIVE REAL-TIME TOOL FOR SOLIDIFICATION, COOLING AND QUALITY CONTROL OF CONTINUOUS CASTING PROCESS

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Abstract

In the continuous casting of steel, there is a variety of dynamic situations, both planned such as changing the steel grade, tundish replacement and unplanned such as breakout system interventions, equipment failure, etc. These situations cause variations of the casting parameters such as of the casting speed, casting temperature, intensity of cooling in the secondary cooling zone, etc. An improper configuration of casting parameters can negatively affect the quality of semi-finished products. A real-time tool based on a fuzzy-predictive control algorithm with the 3D dynamic solidification model was created. The real-time predictive control simulation is provided with the use of massive GPU source-code parallelization. Software implementation and integration to the Level 2 automatization system is also shown. Results are presented for the case with a casting-speed drop and for a slab caster with 17 cooling loops in the secondary cooling zone.

Keywords: Secondary cooling, fuzzy control, model predictive control, GPU calculation

1. INTRODUCTION

Undoubtedly, the continuous casting (CC) technology is a major way how the steel is cast in the world. From the literature reviews one can find that CC process has today more than 97 % of the world steel production ratio [1]. There are more reasons why the CC process reaches such huge achievement. The CC in comparison to the obsolete ingot casting, increases the production efficiency, steel quality, operation safety, and improves many other aspects during the production. In spite of the fact that CC is already matured technology, there are still efforts from many steelmakers to make the production more effective, more automatized, increase the steel portfolio by casting special steels such as higher-strength grades, steels for acidic environments, steels for the offshore technology, high alloyed tool steels, etc. [2]. Many of these challenges can be solved by using computer heat-transfer, stress-strain and micro-macro segregation numerical models [3, 4, 5]. Computational capabilities in these days easily handle with the complex 3-D very fine mesh simulations which can run even faster than the real time. The combination of these numerical models with optimization/decision-making/optimal-control algorithms gives an opportunity for real time optimal self-sufficient control system for the CC process [6, 7, 8]. The optimal control can be based on many requirements such as to preserve or increase the quality of steel, maximizing productivity, minimizing production costs (e.g. water consumption), and their combinations.

This paper deals with the original 3-D solidification model and advanced optimal-control tool for the steel quality and casting productivity improvement. The coupled complex numerical model and optimal-control simulation have high computation demands on classic CPU hardware. The one possible way how to use presented approach for the real time control of CC process is to use massive parallelization by using graphics processing units GPU.

2. SOLIDIFICATION MODEL

The mathematical formulation of the solidification model is based on the governing equation of transient non-linear heat conduction problem, which is also called the Fourier-Kirchhoff equation. The detailed mathematical description of the solidification model can be found in [8]. The client part of the new generation of the solidification model is shown in **Figure 1**. The solidification Brno Dynamic Solidification Model (BrDSM) can be used for off-line and on-line simulations, it can calculate steady-state as well as transient problems and it can be synergically integrated to the Level 2 automatization system.

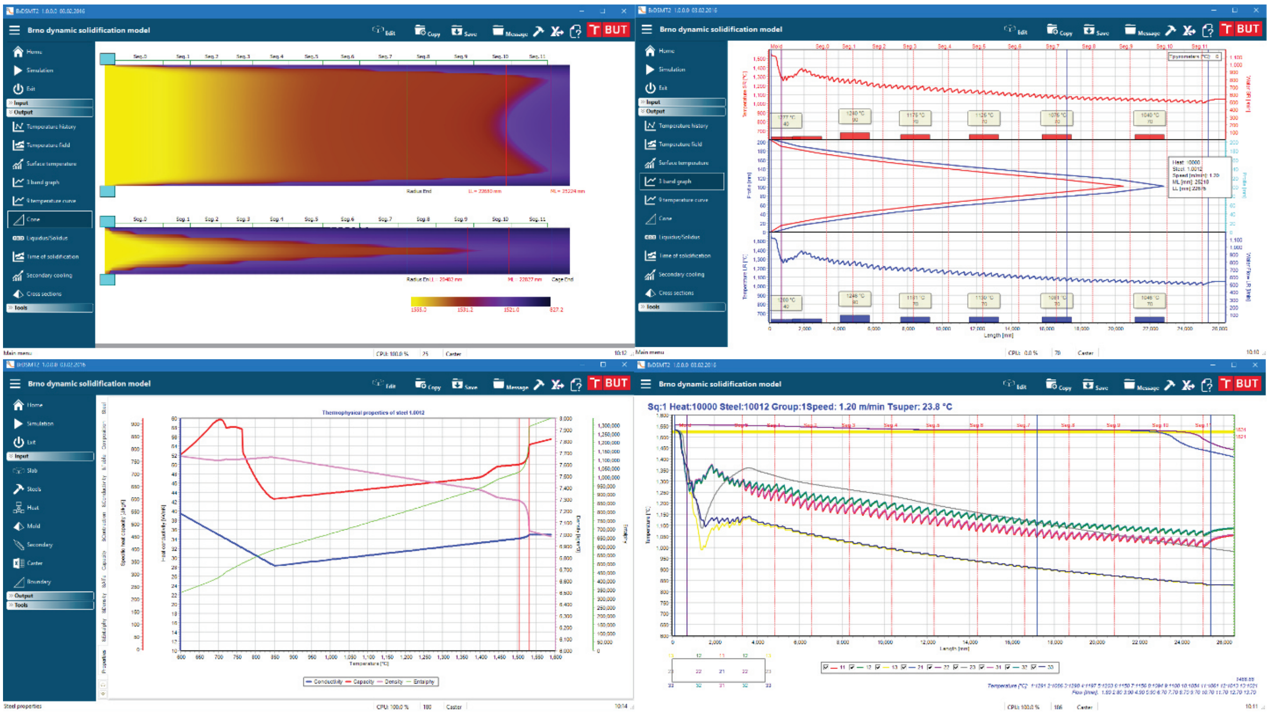

Figure 1 Solidification model interface

2.1. Thermophysical properties and IDS

The thermophysical parameters such as the thermal conductivity, density, specific heat capacity and the enthalpy are all strong functions of the temperature. The solidification model has a large database of grades of steel precomputed from the chemical compositions by using the solidification analysis package IDS [9]. The IDS (InterDendritic Solidification) is a thermodynamic-kinetic package, which simulates phase changes, compound formation/dissolution and the solute distribution during the solidification of steels and during their cooling /heating process after the solidification. The package also simulates solid state phase transformations related to the austenite decomposition process (ADC) at temperatures below 900 / 600 °C, and it calculates important thermophysical material properties (enthalpy, thermal conductivity, density, etc.) from the liquid state to the room temperature. These data are needed in other models, such as in heat transfer and thermal stress models, whose reliability highly depends on the input data itself. The calculations of IDS have been compared with many experimental solidification related measurements showing a good agreement [10].

The new version of IDS was announced and will be soon released. This new version of IDS will allow for calculations of thermophysical parameters also in the case of reheating (so called zig-zag). It means that numerical results are even more accurate that in the previous numerical models as reheating is common in CC process.

2.2. Boundary conditions

The determination of the boundary conditions is provided by using laboratory experiments. Because the laboratory experiments are generally expensive, a lot of authors use empirical relationships for the determination of boundary conditions [4 - 7]. However, for instance in the case of air-mist nozzles the results are not sufficient because they do not include the Leidenfrost effect, the strand surface temperature, etc.

The measurement part of the research is carried out by Heat and Fluid Flow Laboratory at the Brno University of Technology. Information about the laboratory and the experiment can be found in [11]. So far mainly the heat transfer coefficient beneath the nozzles was measured, but new unique measurements of heat transfer coefficient beneath the rollers are in preparation.

2.3. Software implementation and parallel computation

The core of numerical model is programmed in C++ which allows for fast calculations. In cooperation with the IDS, the model allows the user for an application of various thermophysical parameters, thus the temperature field can be calculated for various steel grades via their chemical composition. The model also has a large database of measured water and air-mist nozzles which can be used for boundary conditions. In the case that measurements are not available for a particular nozzle, empirical formula with a split-normal distribution is used.

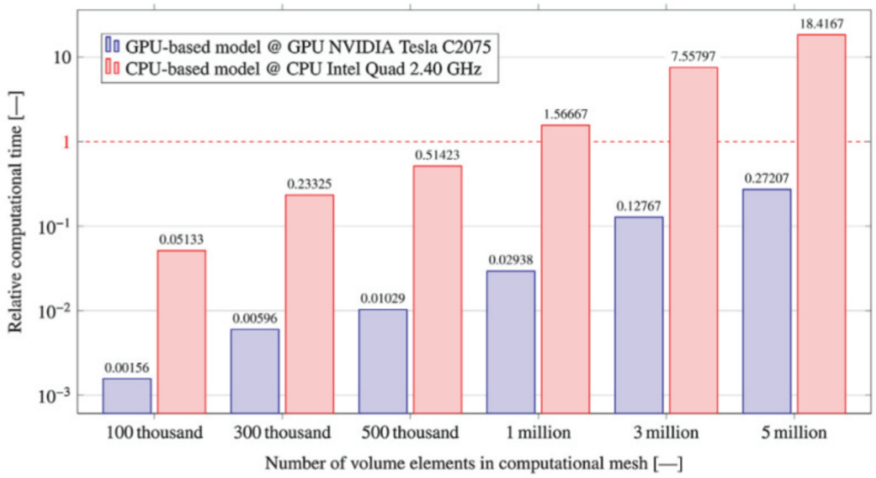

Figure 2 GPU - model benchmarking - relative computational time [12]

The time derivate in the numerical model is replaced by the explicit discretization schema which easily allows for massive parallel decomposition. As already mentioned, there is a natural effort to speedup numerical models in order to utilize these models for on-line control and regulation of CC process in real time. Currently used commercial dynamic models use traditional single or multi-core CPU computing. However, various computing problems, which can be parallelized, are possible to solve on graphics processing units (GPUs). The dynamic solidification model presented in the paper was implemented and developed with the use of CUDA C/C++. In order to compare the computing performance, a series of benchmark tests was performed. The CPU-based model was running on a computer with Intel Core 2 Quad processor with four cores of 2.4 GHz and 6 GB RAM memory. The GPU-based model was tested on a computer with the GPU device NVIDIA Tesla C2075, which includes 448 CUDA cores of 1.15 GHz and 6 GB RAM memory. Results of computing performance tests are shown in **Figure 2**. At the vertical axis, there is a relative computational time which means that the computing time is divided by the simulated time period. For instance the numerical CPU model with one million nodes is 1.56-times slower than the real time, but on the GPU the simulation runs faster than the real time. Even for five million nodes the GPU model runs faster than the real time [8].

2.4. Solidification model validation

The solidification model without a proper validation should not be used for the real CC process control. The presented model was validated through the years by surface temperature (pyrometers and temperature scanners) measurements and solidification point position (radioisotope method) measurements [12]. For instance the long-term verification for slab casting was carried out in EVRAZ Vítkovice Steel, a.s. and for the billet casting in Třinecké Železárny, a.s in the Czech Republic.

3. FUZZY LOGIC AND MODEL PREDICTIVE CONTROL REGULATION

In order to improve the quality of steel and increase the productivity of the CC process, the Fuzzy based controller was created. Unlike classic PID regulators, the Fuzzy regulator gives us better control utilization, higher stability with less overshoots, flexible knowledge base design, fast response on dynamic changes and nonlinear control [8].

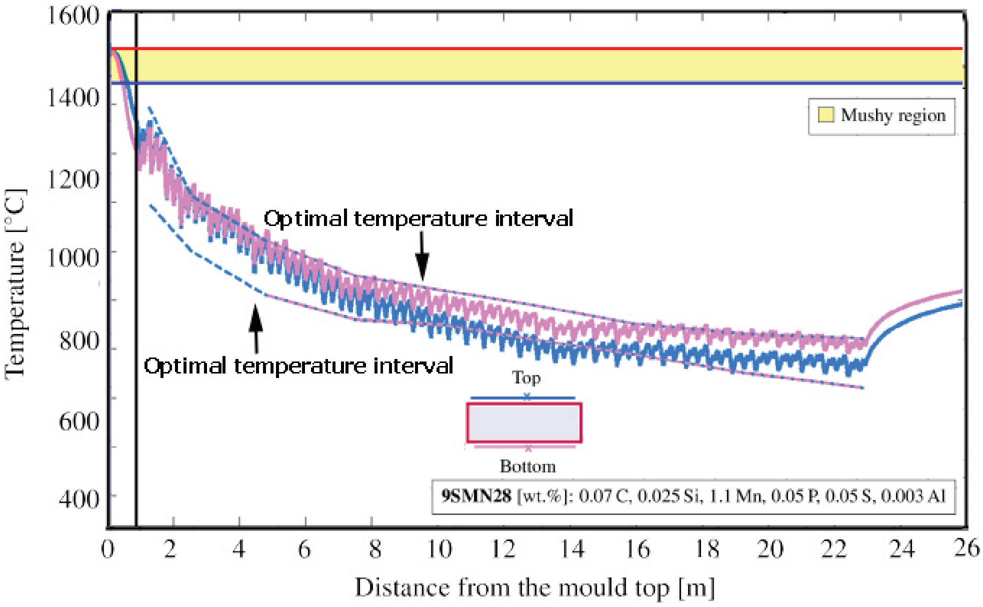

Figure 3 Slab caster temperature history at the top and at the bottom surfaces including the allowed temperature intervals

The inputs for the regulation algorithm are the surface temperature intervals which should correspond with optimal steel surface quality and the position of the solidification point which affects the inner steel quality. The example of temperature intervals and the average surface temperature which satisfies these intervals can be seen in **Figure 3**. Detailed description of presented fuzzy regulator can be found in [8].

The solidification model, due to of GPU acceleration, allows us to calculate the future states of the temperature field. In combination with the fuzzy regulator, the model-based predictive control (MPC) can be created [6]. The MPC utilizes the model of the process to predict the behavior of the system resulting from the changes in the inputs and to evaluate the consequences of these modifications. We deal with the Scenario approach where the fuzzy regulator picks the best solution. The Scenario approach in this situation means to recalculate the solidification model many times, which increases the computational time significantly. However, by using the developed very fast GPU numerical model the Fuzzy-based Model Predictive Control (F-MPC) brings elegant, robust and powerful solution how to optimally control the CC process.

3.1. Integration of the F-MPC-BrDSM to Level 2 of automatization system in steelworks

An integration of the discussed F-MPC-BrDSM to the Level 2 of the automatization system is carried out in the cooperation with ASM Automation Company (www.asmautomation.com). The overall software implementation is shown as a block scheme in **Figure 4**.

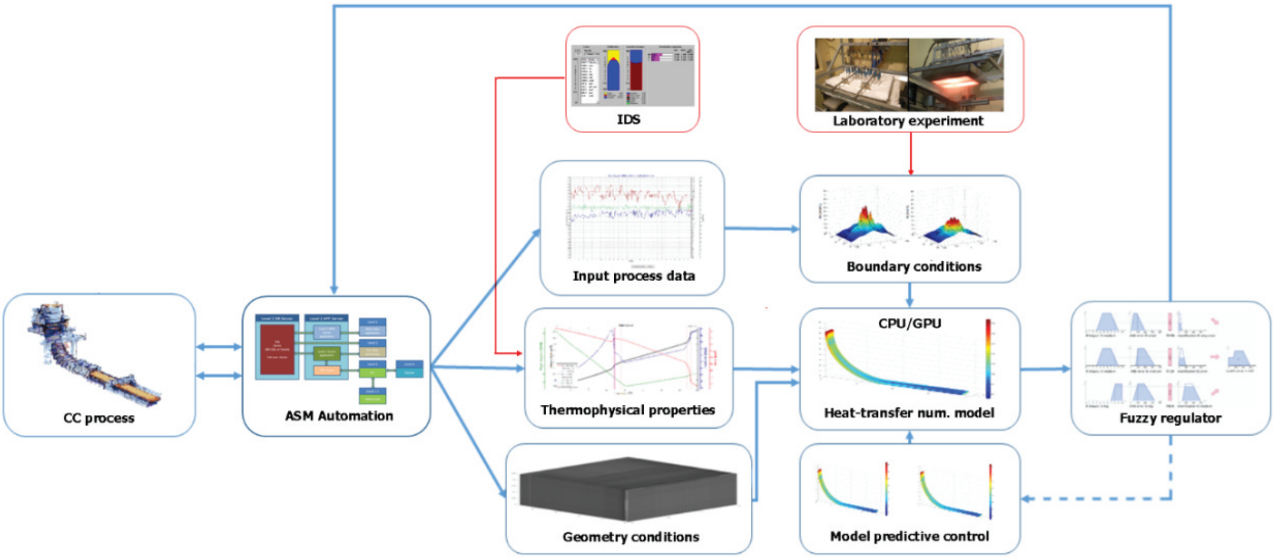

Figure 4 Block scheme of software implementation

4. RESULTS AND DISCUSSION

The fuzzy regulator was tested for many different fuzzy parameters, for different temperature and casting speed constraints, for different caster and slab geometries, and for different steel grades. This section shows an example of the setting of constraints and related results. The scenario simulates 1 hour slab casting process where a drop of the casting from 1.9 to 1.2 m / min happens at time 30 min and the increase of the casting speed from 1.2 to 1.9 m / min occurs at time 40 min. The simulation is provided for two cases; first case simulates a situation without a regulation intervention while the second case shows the regulation intervention of the F-MPC regulator. The simulations are provided for the caster with 17 cooling loops in the secondary cooling zone where control points are placed behind each loop.

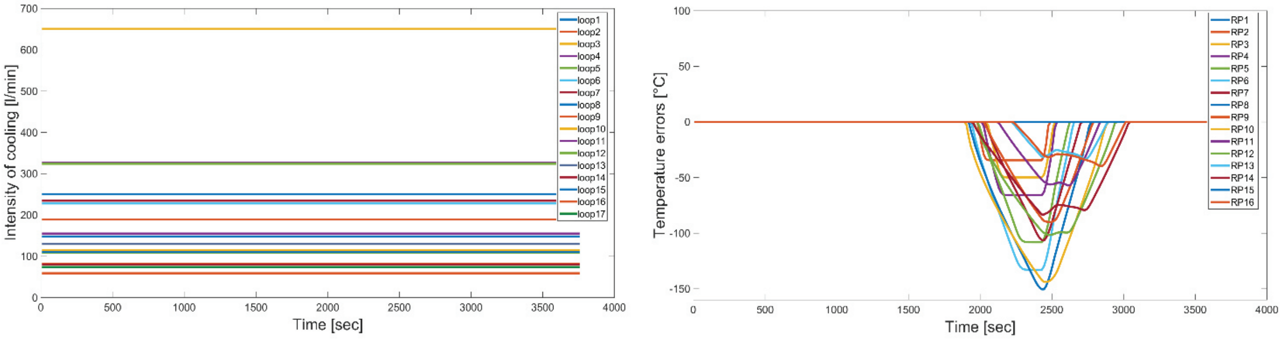

Figure 5 Case with no regulation: left - Water flow volumes, right - Surface temperature errors

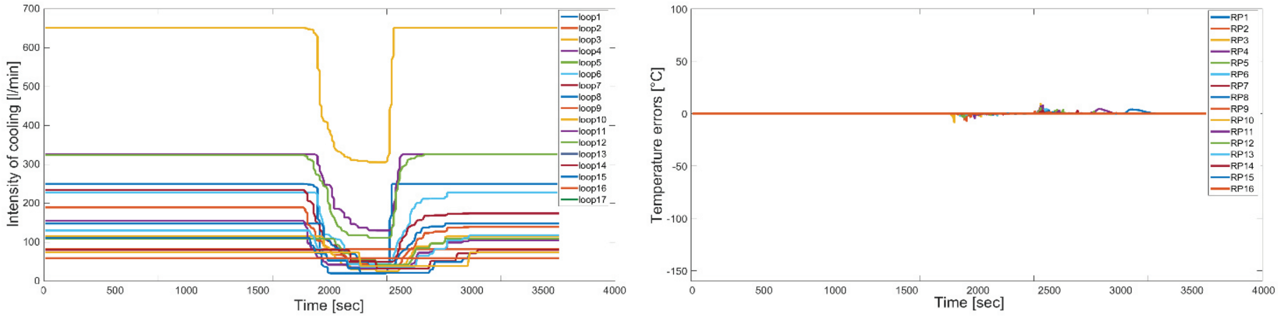

Figure 6 Case with fuzzy-MPC regulation: left - Water flow volumes, right - Surface temperature errors

From the results, **Figure 5 - 6**, are clear that the F-MPC reached very good results, the temperature errors are negligible in comparison with the situation without the regulation. The prediction interval of MPC was set to the future 15 sec. This interval can be longer which would smooth the results. On the other hand the temperature errors can be larger. The user has to set some compromise between smoothness of control and temperature errors. In order to compare the execution times, both simulated cases were carried out with the single CPU. Average execution time for 1 hour simulation (testing cases) without regulation was approximately 27.25 min, while the use of the F-MPC controller simulation takes 47.20 min. It was also mentioned above that the use of the MPC prolongs the computation time. In case that all these simulations should be calculated for finer meshes, the application of GPU model would be necessary in order to obtain results faster than the real time goes by.

5. CONCLUSION

The paper presents the advanced 3-D transient solidification model (BrDSM), its extension to the GPU version, its validation and the possibility for advanced control algorithms based on the fuzzy logic and the model predictive control (F-MPC). The solidification model is general by using the IDS solidification model and is highly accurate due to extensive nozzle measurements in the Heat and Fluid Flow Laboratory. Massive parallelization on the GPU allows us to calculate numerical models with millions of nodes faster than the real time. The cooperation with ASM Automation Company presents a very elegant solution how to integrate the mentioned model to the Level 2 of the automation system. Moreover, to increase the quality of steel, the fuzzy regulator was created to establish appropriate cooling intensities for different casting speeds and casting temperature conditions; to optimally react to dynamic changes of process parameters; and to avoid and prevent liquid steel breakouts by monitoring the position of the solidification point. The regulator was tested for different casting conditions and parameter setting. The calculation with the F-MPC prolong the execution time but in combination with the GPU numerical model, the optimal regulation can be found faster than the real time goes by. This solution brings the real-time regulator which can efficiently solve dynamic changes which occur in the real CC process. The system concept is universally designed to optimally control any slab or billet CC processes and it can be used for maximizing the productivity and increasing the final steel quality.

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