New Challenges in Modelling and Secondary Cooling Control of Continuous Steel Casting

J. Stetina, L. Klimes, T. Mauder, Brno University of Technology, Czech Republic

Contact Data
J. Stetina, Faculty of Mechanical Engineering, Brno University of Technology,
Technicka 2896/2, 616 69 Brno, Czech Republic, stetina@fme.vutbr.cz, tel./fax: +420 514 143 269

Summary
In recent years, there is a dominant trend for the utilization of dynamic solidification models in process and quality control of continuous steel casting. A significant effort has been done in case of control of secondary cooling where water and air-mist nozzles are used. Both simple and sophisticated control and regulation methods are nowadays used for the optimal control of secondary cooling. The paper presents our recent development of advanced control methods based on the fuzzy logic and model predictive control approach. Cooling control by means of the cooling curves and of the PID regulator was implemented in order to evaluate the control capabilities of developed tools. The presented control solution represents a combination of a transient multidimensional numerical model of temperature fields for continuous steel casting and advanced control algorithms. The study case with a temporary drop of the casting speed, which is typical in case of the intervention of the breakout prediction system, was used to evaluate control capabilities of presented algorithms. The results show that our control and regulation algorithms are very efficient tool for the continuous casting control. Applicability of the developed algorithms was tested in a Level 2 implementation of ASM Automation Company, which is our sole implementation partner, and robust control behaviour was observed.

Key Words
Continuous steel casting, secondary cooling control, cooling curves regulation, fuzzy regulation, PID regulation, model predictive control

Introduction
Continuous steel casting is nowadays a technology used for the production of about 97% of steel. In recent years, there is an increasing effort to properly control and regulate the secondary cooling of continuous steel casting. This aim is due to the well-known fact that the quality and structure of cast steel is highly dependent on the heat withdrawal intensity from the strand and its homogeneity. An attention of steelworkers is especially paid to dynamic cases in which casting conditions considerably vary in time, mainly the casting speed. Such a dynamic situation can be, for example, an intervention of the breakout prediction system, an abrupt breakdown of some part of the casting machine, or a replacement of a tundish.

Several control methods and approaches have been adopted and applied to control the secondary cooling [1]. An essential element of the control system is usually the numerical model of transient temperature field of cast strand. These models, referred as dynamic solidification models, are utilized as numerical sensors by control algorithms. A dynamic solidification model provides information on temperatures within the strand and on the solidification. Many papers related to the development of numerical models were published, see, e.g. [2]. Such computer models are usually based on the finite difference, finite element, or control volume methods.

The simplest approach, still often used, is the control of water flow volumes within the secondary cooling according to the casting speed, frequently in linear manner. This method is referred to as the control by means of the cooling curves [3]. The PID regulation is one of more sophisticated control methods and it is rather frequently used in the control of continuous steel casting [4]. A number of implementations are based on PID, but enhanced and tuned up. For example, Wang [5] enhanced the PID controller by means of swarm optimization. Liu and Xie [6] used fuzzy self-adaptation to the PID controller.

However, the mentioned cooling curves and PID methods often behave poorly, mainly due to the nature of their regulation. For example, in case of PID regulation, the actual process behaviour (and its future progress) is controlled according to its past. Researchers therefore tend to implement more advanced control algorithms to overcome these disadvantages. Neural networks [7], swarm optimization [8], fuzzy logic [9], or adaptive control [10] are among these advanced techniques.

The aim of the paper is to examine and compare basic control techniques – the cooling curve method and the PID regulation – with the developed two control systems based on the fuzzy logic and the model predictive control. The study case with a temporary drop of the casting speed is used for the comparison of control methods. Results show that the developed tools represent efficient control algorithms for secondary cooling providing better control behaviour than widely used basic control methods.

Mathematical Model of Temperature Field of Continuously Cast Steel Strands

As already mentioned above, the developed two control algorithms presented in the paper use the numerical model of the temperature field of cast strand as the numerical sensor of a real casting machine [11]. The numerical model is hence a crucial part of control systems and the accuracy and reliability of the model directly influence the accuracy of the control.

Our implemented numerical models [12, 13] have been assembled by means of the finite difference and control volume methods. The heat transfer and solidification of a strand is described by the Fourier-Kirchhoff equation [14]

$$\frac{\partial H}{\partial t} = \nabla \cdot (k_{\text{eff}} \nabla T) + v_{casting} \frac{\partial H}{\partial z} \quad (1)$$

where the volume enthalpy H is used for modelling of latent heat of phase changes: transition from liquid to solid and phase transformations in solid state as well. The volume enthalpy can be defined as [14]

$$H(T) = \int_0^T \left(\rho c - \rho L_f \frac{\partial f_s}{\partial \vartheta} \right) \mathrm{d}\vartheta \quad (2)$$

The numerical models are transient and an explicit formulation was used for the derivation of governing equations. The models are fully 3D and they provide information about temperature for the complete strand, i.e. from the mould, secondary and tertiary cooling to the cut-off torch. The scheme for the billet casting machine is pictured in Figure 1.

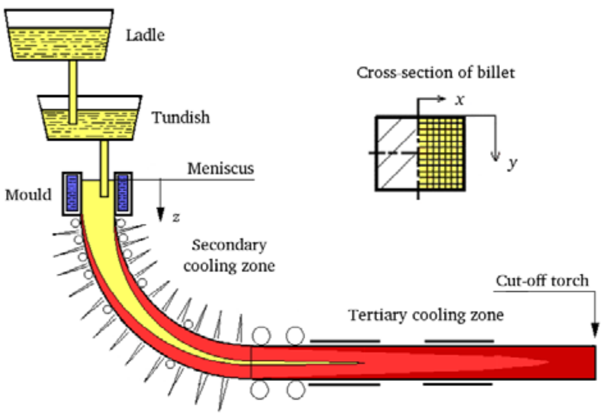

Figure 1: Scheme of the billet casting machine

There are many issues related to numerical models for continuous casting. Mass transfer and fluid flow are usually neglected, or can be taken into account by a simple effective thermal conductivity method. Another approach is to model in detail the fluid flow phenomena in the liquid core of a strand, which makes sense especially when a detailed study of the mould is considered. The determination of heat withdrawal from the mould and from the secondary cooling is another important issue, usually solved by experiments [15, 16, 17]. This was also the case used in the developed models. We refer the reader to [12, 13] for further particular information on numerical models of continuously cast strands, on determination of boundary conditions, and on particular computer implementations of these models which are used for simulations in the paper.

Regulation algorithms for secondary cooling control of continuous casting

The aim of the paper is to compare our developed advance control algorithms based on fuzzy logic and model predictive control with other common control methods (cooling curves method and PID regulation) that are often used in steelworks. A brief description of these algorithms follows.

There are many approaches how to optimally control the continuous steel casting. The most common way is the use of so-called cooling curves. Cooling curves are functions of some casting parameters and they usually determinate the water flow volume through each cooling zone according to the casting speed. For the casting machine and for the study case presented in the paper, we used the cooling curves shown in Figure 2. Since the used casting machine is a real casting machine operated in steelworks in the Czech Republic, the presented curves are actual cooling curves that are used in practice. The use of the cooling curves is a straightforward and rather easy approach, but they do not behave well in dynamic situations due the system delay.

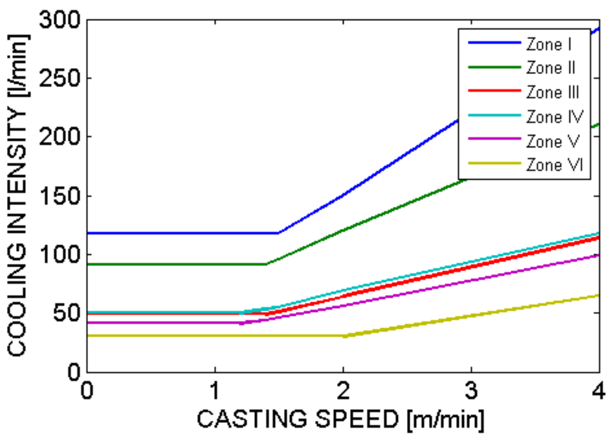

Figure 2: Cooling curves

PID controllers and regulation are also often used, see, e.g. [4, 1]. The main idea of PID is to regulate the process by means of the decomposition of the objective function to three parts – proportionally, and according to its derivative and integral. The PID controller separately regulating the cooling intensity according to the temperature at the end of each cooling circuit is shown in Figure 3.

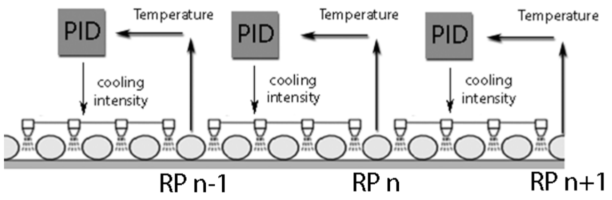

Figure 3: PID regulation of secondary cooling

Advantages of PID control are a relatively easy implementation, in general only three parameters P, I, and D to be set up and an automatic parameter tuning mechanism. The main drawback of PID is, however, its non-convenience for the control of non-linear systems and its use in systems with fast changes of process parameters. Furtmueller and del Re [18] described and discussed challenges and control issues of the PID use for the continuous casting and they also analyzed limitations of PID control.

The regulation approach based on the fuzzy logic is successfully implemented in many engineering and scientific applications. An application of the fuzzy approach in the control of continuous casting is rather rare [13, 19], but in comparison to PID control the fuzzy logic offers better control performance, smaller overshoots, faster response, robustness and stability. General drawbacks of the fuzzy logic are time needed for system learning, difficult setting of many parameters and many possibilities for system configuration. The regulation scheme of the fuzzy logic is shown in Figure 4. Unlike the PID controller the fuzzy logic regulator evaluates an actual situation in the whole domain and assesses the changes of cooling intensity according to the strand temperatures at control points. The fuzzy regulator is defined as combination of linguistic variables and linguistic rules. We refer readers to [13] for more information.

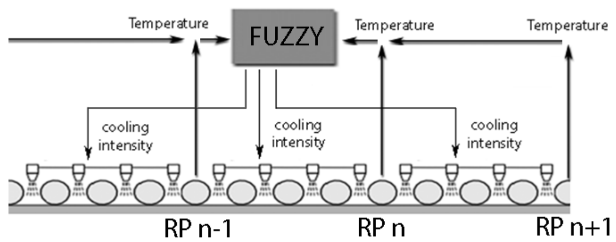

Figure 4: Fuzzy control system in secondary cooling

The model predictive control is another advanced approach successfully implemented and used in many engineering applications [20]. Some implementations in control of continuous casting of steel also exist [21, 22]. The main idea of the model predictive control is to use the computer model as a numerical sensor for the prediction of the future thermal behaviour of the strand. In comparison to the PID controller, the model predictive approach controls the process according to forward prediction of the future behaviour under a certain control strategy whereas the PID controls the system according to its past. The model predictive control offers a precise and high-performance control of a process. This approach is also stable and robust. A most significant drawback of the model predictive control is a need for repetitive forward evaluations of the controlled system which might be computationally very demanding. However, a massive parallelization of the model by means of its launching on graphics processing units can effectively overcome this problem [12], see Figure 5. Such a huge parallelization allows operating the model predictive control system in real time. We refer readers to [21] for further details about the model predictive controller used in the paper.

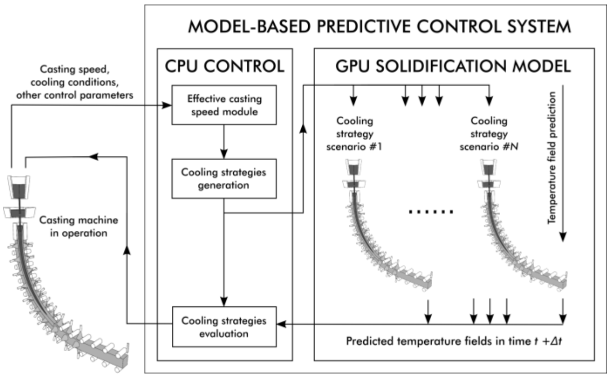

Figure 5: Scheme of parallel model predictive system

Study Case and Regulation Approach

Real casting conditions were used for the configuration of the study case. The numerical models were configured for square billets with dimensions of 150 × 150 mm. The radial casting machine has the mould with the heat withdrawal power of about 1 MW. The secondary cooling has 6 independent cooling circuits and contains about 200 cooling nozzles.

A low carbon steel with 0.18 wt. % C was considered for the study case. This steel has the solidus and liquidus temperatures of 1,457 °C and 1,515 °C, respectively, and the temperature of 1,549 °C was set to its casting temperature. The grade is normally cast with the casting speed of 2.8 m/min. Figure 6 shows the steady state temperature field for mentioned casting parameters. This field was considered as optimal and the optimal mean surface temperatures in each cooling circuit were calculated from it. Figure 6 also shows the regulation points (RPs) in which the temperatures were used for regulation.

As for the study case used for the examination of different control approaches, a situation with a temporary drop of the casting speed was selected: casting speed drop from 2.8 m/min to 1.5 m/min was assumed and then the casting speed linearly rose to the value of 2.5 m/min within 5 minutes. Finally, the casting speed was immediately increased to the initial value of 2.8 m/min. The used casting speed as a function of time is plotted in Figure 7.

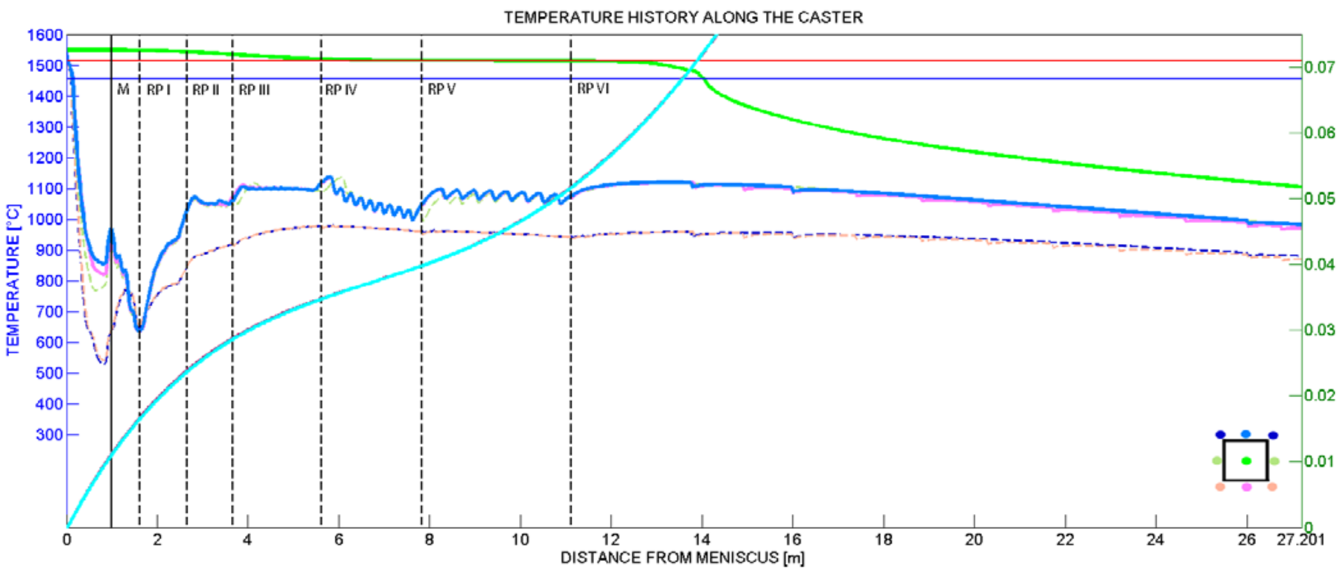

Figure 6: Steady state temperature field, which was considered as optimal solution for regulation

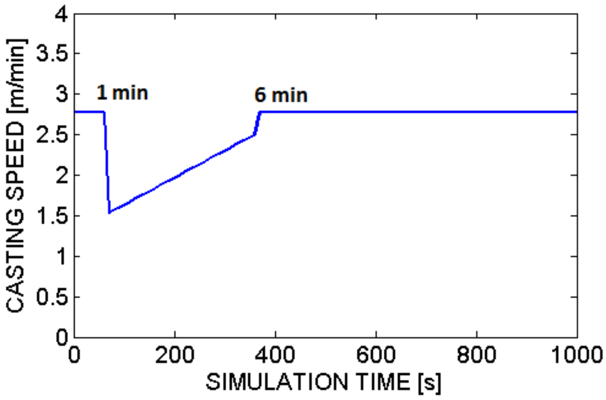

Figure 7: Study case – casting speed

The regulation approach was based on a combination of both the numerical model of temperature field and regulation algorithms. Regulation algorithms were used as the supervision system and worked in a closed-loop, see Figure 8. The supervision system therefore uses data provided by the numerical model of temperature field and then adjusts the water flow volumes in secondary cooling. The mean surface temperature was set up for each cooling circuit. This can be generally done according to user requirements. For the investigated study case we used the mean temperatures from the steady state solution.

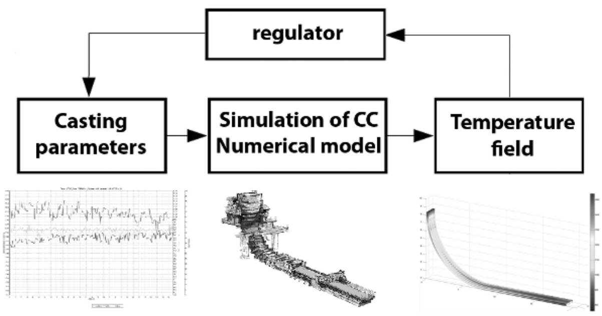

Figure 8: Scheme of regulation

The aim of the regulation was to determine the time-dependent water flow volume rates through 6 circuits of secondary cooling so that the average surface temperatures in cooling circuits would remain constant, if possible. This means that the thermal state of the strand cast with the casting speed of 2.8 m/min in the steady state regime was considered as the optimal solution of regulation, see Figure 6.

Results and Discussion

The regulation problem with a drop of the casting speed was controlled by means of four control methods described in the foregoing paragraph. A control with no change in water flow volume rates was also calculated and it confirms a necessity for the process control. For each control strategy two figures are presented: the time dependent water flow volumes through all cooling circuits, and the time-dependent temperature errors that evaluate the control process. The temperature error here means the difference between the required mean surface temperature in a particular cooling circuit and the actual mean surface temperature under a particular control strategy.

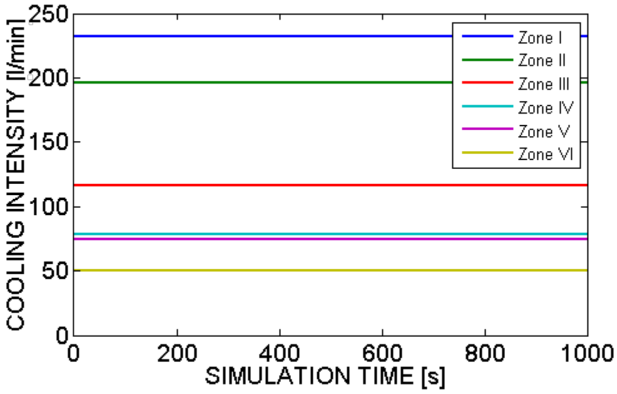

Figure 9: Water flow volumes: case with no regulation of secondary cooling

Figures 9 and 10 show the water flow volume and the temperature errors, respectively, for the case with no control, i.e. no change of water cooling. As can be seen from Figure 10, constant water flow volumes through secondary cooling cause a significant and extensive subcooling of strand surface, locally even about of 250 °C. This is obviously caused by a more intensive heat withdrawal from the strand due to a lower casting speed. The presented subcooling is strongly undesirable since it can lead to the formation of cracks and defects. Some control of secondary cooling is therefore definitely needed.

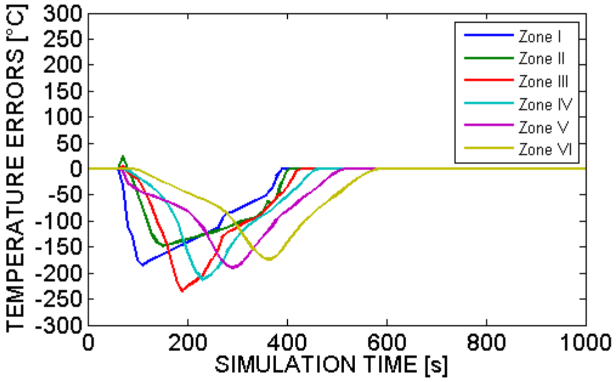

Figure 10: Surface temperature errors: case with no regulation of secondary cooling

Figures 11 and 12 present the water flow volumes and the corresponding surface temperature errors, respectively, for the case with control by means of the cooling curves shown in Figure 2.

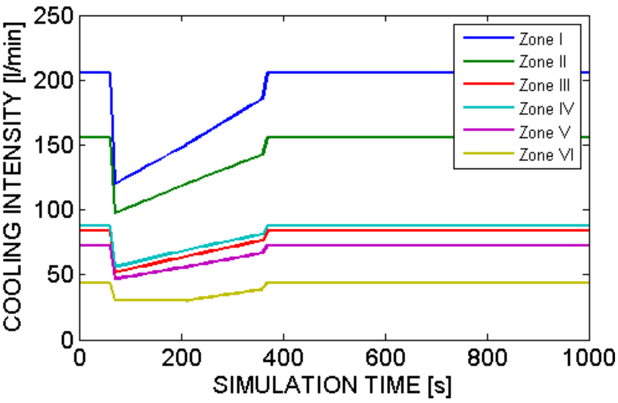

Figure 11: Water flow volumes: case with control by means of cooling curves

In Figure 11 one can see a typical cooling control in case of cooling curves. It is apparent that the change of water flow volume rates takes place only in time period when the actual change of the casting speed occurs. The corresponding surface temperature errors can be observed in Figure 12. The overheating is present mainly in zones I and II (closest zones to the mould), but the control is better than in case with no regulation (cf. Figure 8 and 9). Moreover, zones IV, V, and VI are still subcooled. The mean surface temperatures fluctuate for almost 7 minutes from the moment when the casting speed initially dropped.

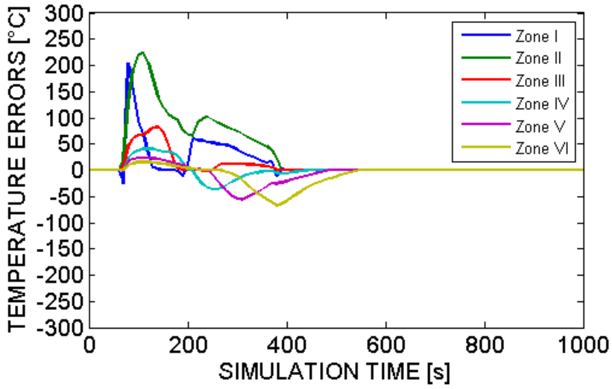

Figure 12: Surface temperature errors: case with control by means of cooling curve

Figures 13 and 14 show results for the control by means of the PID regulation. As can be seen in Figure 13, the PID regulator controls and modifies the water flow volume rates not only in the time period where the temporary drop of the casting speed takes place, but also in later times when the casting speed is back to its initial value. For example, the flow rate in zone VI, which is the furthest zone from the mould, is regulated almost 3 minutes after the casting speed is back to its initial value. Mean surface temperature errors shown in Figure 14 behave quite well.

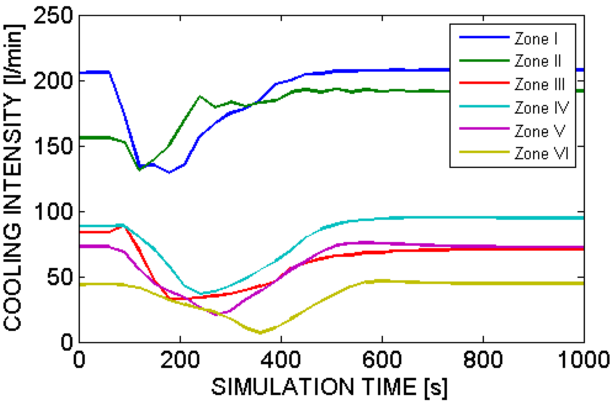

Figure 13: Water flow volumes: case with control by means of PID regulator

The subcooling and overheating are still present, but their amplitudes are lower than in case of the control by means of cooling curves. The mean surface temperature errors occur for a shorter time period of about 3 minutes.

Figures 15 and 16 present the results for the secondary cooling control by means of the developed fuzzy logic regulator. Similarly as in the case of PID control, the fuzzy regulator modifies the water flow

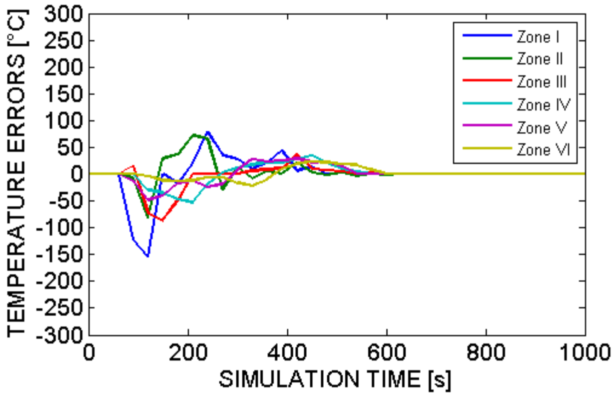

Figure 14: Surface temperature errors: case with control by means of PID regulator

volume rates not only in the actual time period with the drop of the casting speed, but also in later times. The time dependent courses of the flow rates seem to be smoother than in case of PID regulation. An interesting point is the regulation of the second cooling circuit (zone II) since the fuzzy regulator performs it in a significantly different manner than the PID regulator does. Moreover, in case of PID regulation the flow rate in the second cooling circuit reaches a new steady state solution that is different to the initial value, see Figure 13. As for the mean surface temperature errors, Figure 16 shows an excellent improvement of temperature fluctuations at the strand surface.

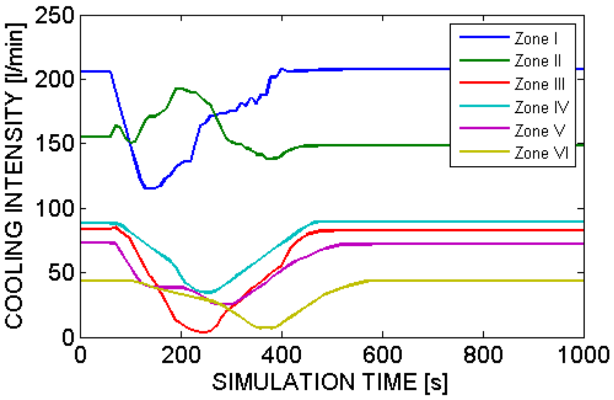

Figure 15: Water flow volumes: case with control by means of fuzzy regulator

Subcooling and overheating of the strand surface is almost eliminated. In comparison to the PID regulation, the temperature errors are significantly smaller and their maximal values peak at about only 50 °C. The fuzzy regulator therefore represents an efficient tool how to maintain the mean surface temperatures almost constant during the temporary drop of the casting speed.

Finally, Figures 17 and 18 present the results for the regulation by means of the model predictive control system. The time dependent water flow volume

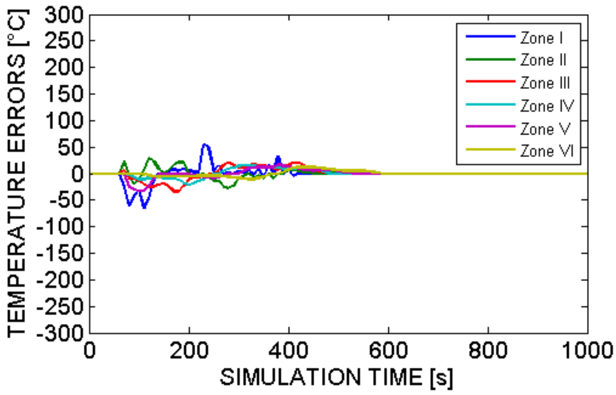

Figure 16: Surface temperature errors: case with control by means of fuzzy regulator

rates shown in Figure 17 are quite similar to those used in the PID regulation. The flow rate in the second cooling circuit (zone II) is initially slightly increased although the casting speed dropped, but then follows a decreasing trend. Similarly to cases of PID and fuzzy control, the regulation of flow rates is performed also in later times when the casting speed is already back to its initial value. As can be seen in Figure 18, the model predictive control serves an excellent control of mean surface temperature. Virtually there is no subcooling and overheating, the mean surface temperatures remain practically constant.

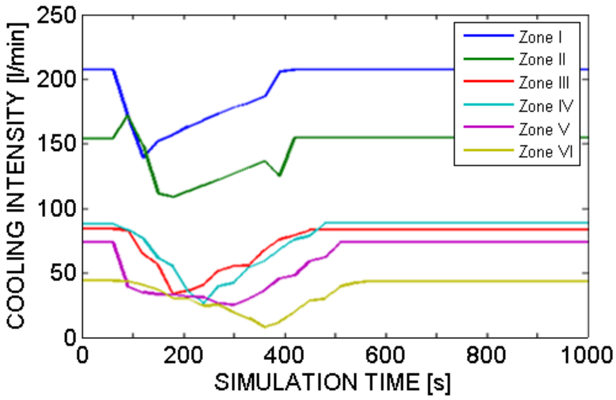

Figure 17: Water flow volumes: case with control by means of model predictive control system

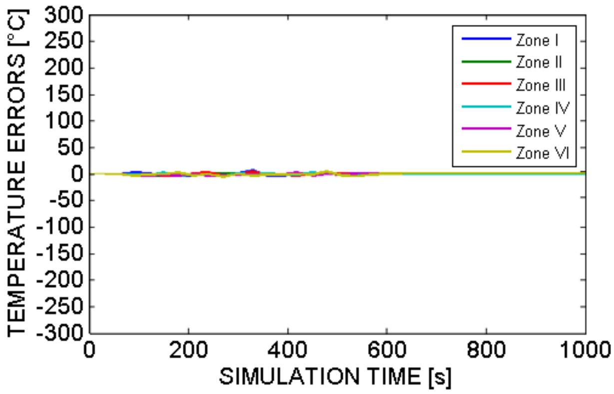

Figure 18: Surface temperature errors: case with control by means of model predictive control system

Proc. 22nd Int. Conf. Mater. Metallurgy METAL, 2013, P. 34–39.
[13] Mauder, T.; Sandera, C.; Stetina, J.: Optimal control algorithm for continuous casting process by using fuzzy logic; Steel Res. Int., *in press,* 2015, DOI: 10.1002/srin.201400213.
[14] Stefanescu, D.M.: Science and engineering of casting solidification; Second Edition, Springer, 2009.
[15] Pyszko, R.; Prihoda, M.; Fojtik, P.; Kovac, M.: Determination of heat flux layout in the mould for continuous casting of steel; Metalurgija, 51 (2012), P. 149–152.
[16] Raudensky, M.; Horsky, J.: Secondary cooling in continuous casting and Leidenfrost temperature effects; Ironmak. Steelmak., 32 (2005), P. 159–164.
[17] Pyszko, R.; Prihoda, M.; Burda, J.; Fojtik, P.; Kubin, T.; Vaculik, M.; Velicka, M.; Carnogurska, M.: Cooling nozzles characteristics for numerical models of continuous casting; Metalurgija, 52 (2013), P. 437–440.
[18] Furtmueller, C.; del Re, L.: Control issues in the continuous casting of steel; Proc. 17th World Congress Int. Feder. Autom. Cont., Seoul, Korea, 2008, P. 700–705.
[19] Tirian, G.O.; Prostean, G.; Rusu-Anghel, S.; Cristea, D.: Adaptive control system of continuous casting process based on a fuzzy logic mechanism; Proc. Int. Joint Conf. Comput. Cyber. Tech. Inform., 2010, P. 379–382.
[20] Tatjewski, P.: Advanced Control of Industrial Processes: Structures and Algorithms; Springer,
[21] Klimes, L.; Stetina, J.: Unsteady model-based predictive control of continuous steel casting by means of a very fast dynamic solidification model on a GPU; Mater. Tehnol., 48 (2014), P. 525–530.
[22] Ivanova, A.: Model predictive control of secondary cooling model in continuous casting; Proc. 22nd Int. Conf. Mater. Metallurgy METAL, 2013, P. 81–86.