COMPARISON OF REGULATION ALGORITHMS FOR SECONDARY COOLING OF CONTINUOUS CASTING PROCESS

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Abstract

The paper presents the use of a solidification model coupled with control algorithms for optimization of secondary cooling. The solidification model provides data to control algorithms, which evaluate an actual thermal state of a strand and control casting parameters such as cooling intensity in secondary cooling zone. The paper aims at our recent development of advanced control methods for secondary cooling. A fuzzy logic and model predictive control approaches are tested and compared to traditional PID regulation and cooling curve control. A study case with a dynamic change of the casting speed, which may occur in production, is used to assess control capabilities of developed algorithms. Simulation results show the developed control and regulation tools are robust and effective for control of secondary cooling in continuous casting.

Keywords: Continuous casting, secondary cooling control, PID, fuzzy regulation, model predictive control

1. INTRODUCTION

Continuous steel casting is used for the production of more than 95% of steel. A great effort has been recently exerted to develop control and regulation algorithms for secondary cooling as the quality of steel is strongly dependent on the intensity of heat withdrawal. An attention is mainly aimed at dynamic cases with unsteady casting conditions. Examples include an alternation by means of the breakout prediction system and the tundish on-the-fly replacement.

A number of control algorithms have been developed and used in the secondary cooling control [1]. These systems usually utilize dynamic solidification models of transient temperature field of cast slabs or billets. Many research papers related to the implementation of dynamic solidification models have been presented, see, e.g. [2]. As for the cooling control, a simple regulation of water flow rates in the secondary cooling according to the casting speed is often used. This approach is referred to as the cooling curves control [3]. The PID control is another control method, which is frequently applied in continuous casting of steel [4]. The methods by means of cooling curves and PID, however, frequently do not provide a proper control. Researchers therefore tend to use control methods with better control capabilities [5]. Neural networks [6], swarm optimization [7], fuzzy logic [8], or adaptive control [9] are examples of such advanced techniques.

The paper aims at the comparison of the cooling curve method and the PID control with our two implemented control approaches underlying on fuzzy logic and model predictive control. A case with a transient change of the casting speed is utilized for the comparison of control algorithms. Results adumbrate that our implemented control systems are effective algorithms for secondary cooling control with a great control behavior.

As mentioned above the presented control systems utilize the dynamic solidification model, which provides the prediction of the temperature distribution of the cast strand. 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 secondary cooling is another important issue, usually solved by experiments [10, 11] and followed by the inverse heat transfer analysis [12]. This was also the case used in the developed models. We refer the reader to [13, 14] for further particular information on the numerical models of continuously cast strands, on the determination of boundary conditions, and on particular computer implementations of the models, which are used for simulations in the paper.

2. REGULATION METHODS FOR SECONDARY COOLING CONTROL

The simplest approach for secondary cooling control is the use of cooling curves. The curves are functions of casting parameters and the casting speed is usually used for the assessment of the water flow rates in secondary cooling. The cooling curves shown in **Fig. 1** are used for the study case presented in the paper. These cooling curves are used in a real caster operation in steelworks in the Czech Republic. In general, the use of curves is simple but the approach often fails in dynamic situations due to system delay behavior.

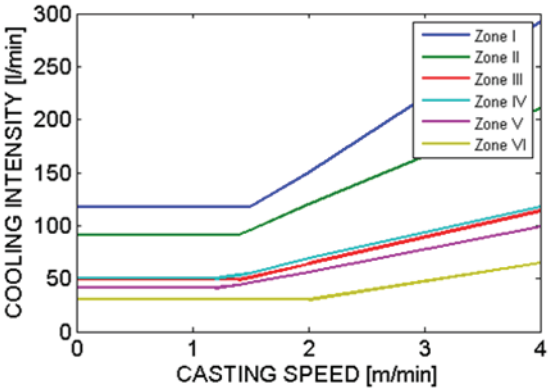


Fig. 1 Cooling curves

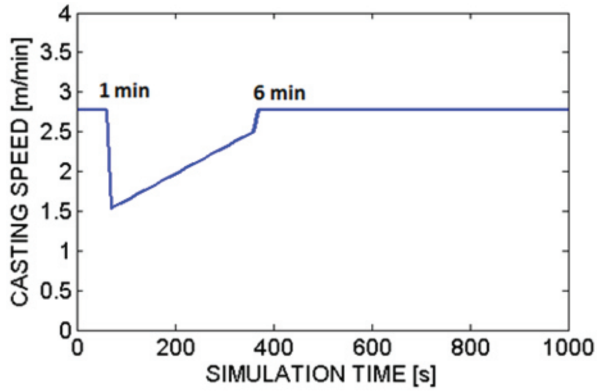
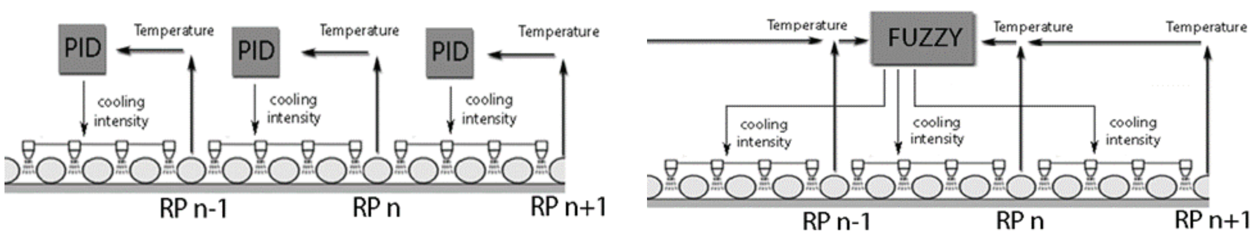


Fig. 2 Casting speed for the study case

The PID control is frequently used for regulation in steelworks [1, 4]. The underlying principle of PID control is the process regulation by means of the decomposition of the objective function into three parts, which contribute to its overall value proportionally and according to the derivative and integral. The PID controller, which regulates secondary cooling according to the surface temperature at the end of each cooling circuit, is shown in **Fig. 3a)**. PID is easy to implement but it is general not convenient for nonlinear system control, which is unfortunately the case of continuous casting.



a) PID regulation of secondary cooling

b) Fuzzy control system in secondary cooling

Fig. 3 Regulation scheme for the PID and fuzzy logic control

The fuzzy logic control is successfully used in a number of applications. The use of the fuzzy logic in the continuous casting control has already been presented [14, 15] and it allows, in comparison to PID control, for better control performance, smaller overshoots, faster system response, and overall stability. Drawbacks of the fuzzy logic include the time necessary for system learning, and tricky setting of parameters. The regulation principle of a fuzzy logic control is shown in **Fig. 3b)**. In contrast to PID, the fuzzy logic algorithm evaluates the behavior of the system in the complete regulation region and determines the cooling setup according to strand temperatures at control points. We refer readers to [14] for more information.

The model predictive control is another sophisticated control method used in a number of engineering applications. The model predictive control has been successfully used in continuous casting control [16, 17]. The main principle of the method is to utilize the model as a numerical sensor, which is used for the estimation of the thermal behavior of the strand in the future under a certain cooling strategy. In comparison to PID, the main feature of the model predictive control is the forward regulation of the controlled system as the PID controller regulates the system according to its behavior in the past. The model predictive control is precise and provides a high-performance control. A drawback is a need for a number of forward model evaluations of the controlled system implying high computational requirements. The massive parallelization of the model by means of graphics processing units can greatly overcome this problem [13], which allows the predictive control system to operate in real time. We refer readers to [16] for more information.

3. STUDY CASE AND CONTROL APPROACH

Actual casting conditions were utilized for the setup of the study case. The dynamic solidification models were configured for casting of square billets having dimensions of 150 × 150 mm. The used radial caster has the mould with the heat withdrawal power of about 1 MW. The secondary cooling of the caster has 6 independent zones within the secondary cooling, which incorporates about 200 cooling nozzles. A low carbon steel grade with 0.18 wt. % C was considered. The steady state temperature field attained when casting with the constant casting velocity of 2.8 m/min was used as the target temperature field for the casting control. The test case consists of a situation with a transient change of the casting speed, which is shown in **Fig. 2**. The control algorithms were used in the supervision system, which utilizes data from the dynamic solidification model and then adjusts the water flow rates in zones of secondary cooling. The aim was to assess the time-dependent water flow rates in secondary cooling in order to preserve the average surface temperatures constant.

4. RESULTS AND DISCUSSION

The study case was solved by means of four control algorithms described in the foregoing section. A control with no change in water flow rates is also presented and it confirms a need for casting control. **Fig. 4** shows the resultant water flow rates in all six zones of the secondary cooling, and **Fig. 5** presents the average surface temperature errors for the control algorithms used.

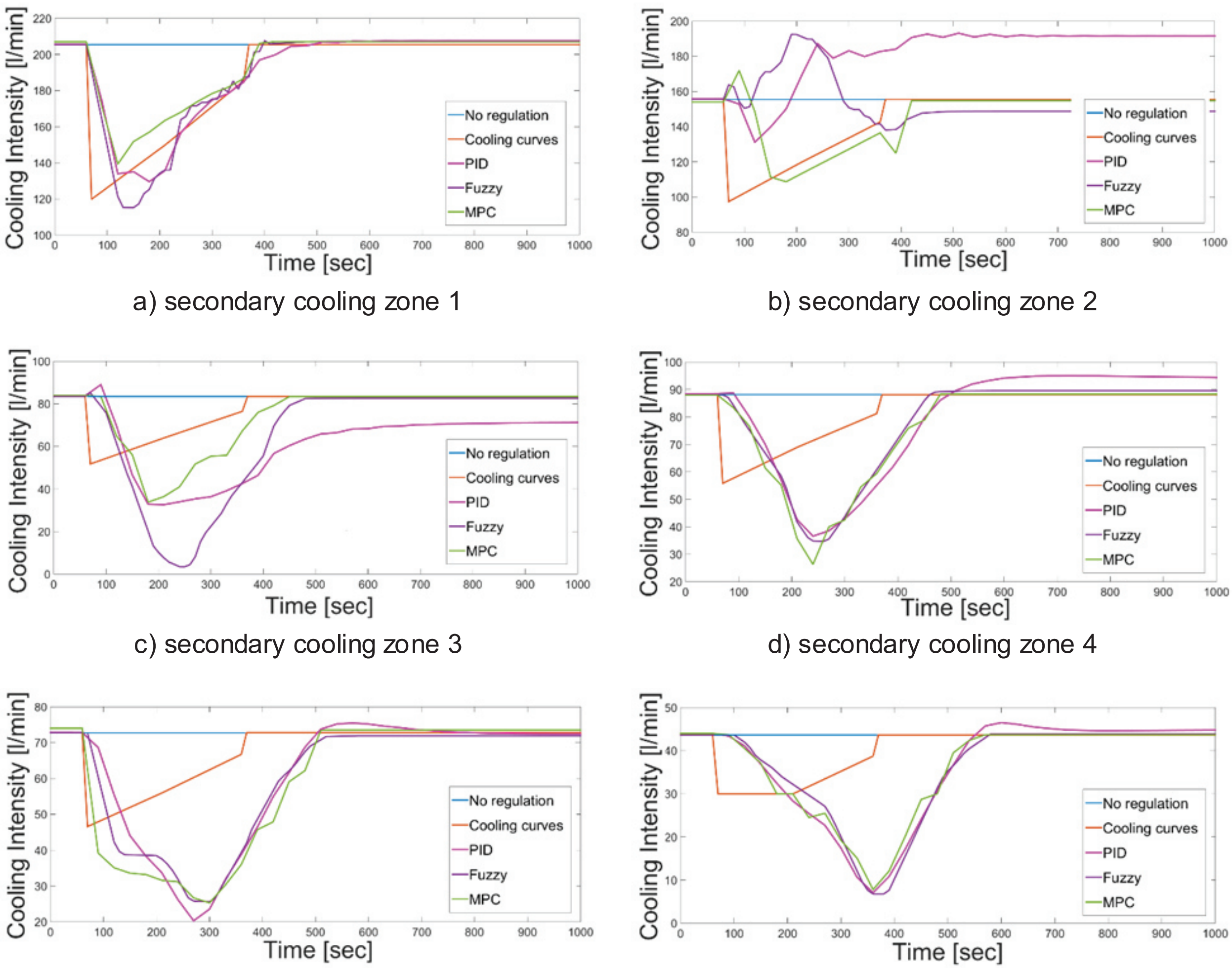
As can be seen from **Fig. 5**, no regulation with constant water flow rates in secondary cooling leads to extensive subcooling of the strand surface, which peaks locally at about of 150 °C for the average surface temperature error. This behavior is not surprising, and it is caused by an intensive heat withdrawal from the strand induced by the temporary lowered casting speed. The integral value of the average surface temperature errors is presented in **Table 1**. Its value, which can be considered as the measure of the control quality, is required to tend to zero. In case of no cooling control, the value of the integral of the average surface temperature error is 3614 °C·s. The subcooling is definitely undesirable as it often causes the formation of defects, such as midway and centerline cracks.

Table 1 Integral of the average surface temperature error

Control approach	No control	Cooling curves	PID regulation	Fuzzy logic	Model predictive control
Integral of average surface temperature error	3614 °C·s	924 °C·s	755 °C·s	265 °C·s	58 °C·s

In **Fig. 4** a typical cooling control for the case with cooling curves can be observed. It is obvious that the modification of water flow rates in secondary cooling occurs only in the period, in which the casting speed actually varies. The dependence of the water flow rates is linear since the cooling curves shown in **Fig. 1** are also linear. The average surface temperature error is presented in **Fig. 5**. In comparison to the previous case, the control by means of cooling curves leads to an overheating, which peaks at about 80 °C almost immediately as the casting speed suddenly drops down. The overheating is also considered to be undesirable as it can cause bulging or even breakout.

As for the PID regulation, the PID system controls and regulates secondary cooling not only within the period when the actual change of the casting speed takes place, but also later in time when the casting speed is already back to its initial value. The average surface temperature error shown in **Fig. 5** undergoes both the subcooling and overheating, but the peaks are smaller being of approximately 70 °C and 30 °C, respectively. The value of the integral of the average surface temperature error presented in **Table 1** indicates a better control than in case of the cooling curve control.



a) secondary cooling zone 1

b) secondary cooling zone 2

c) secondary cooling zone 3

d) secondary cooling zone 4

e) secondary cooling zone 5

f) secondary cooling zone 6

Fig. 4 Water flow rates in secondary cooling zones determined by means of distinct control approaches

Analogously as for the PID control, the fuzzy controller modifies the water flow volume rates not only within the period with the actual drop of the casting speed, but also later in time when the casting speed is returned to its initial value. The time dependent flow rates presented in **Fig. 4** seem to have a smoother course than they have in case of the PID control. A distinct behavior is presented for the water flow rate in the second cooling zone 2 since the fuzzy regulator controls it in a rather different manner than the PID controller. Moreover, in case of the PID control the water flow rate in the second cooling circuit is regulated to a new optimal solution, which differs from the initial value. The average surface temperature error for the fuzzy regulator presented in **Fig. 5** shows a very good improvement of temperature fluctuations at the strand surface. This is also reflected in the value of the integral of the average surface temperature error in **Table 1**, which is 265 °C·s. Subcooling and overheating of the surface is almost eliminated. In comparison to the PID control, the average temperature error is distinctly smaller and it peaks approximately at 15 °C.

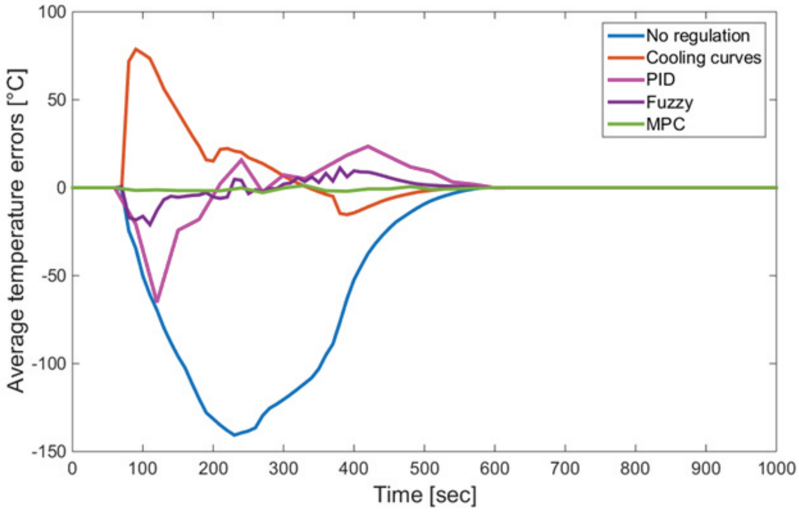


Fig. 5 Average surface temperature errors for distinct regulation approaches

The last presented control approach consists of the model predictive control system. The time dependent courses of water flow rates shown in **Fig. 4** are similar to those determined in case of the PID control. The water flow rate in the cooling zone 2 slightly increases at the beginning although the casting speed drops, but then it has a decreasing trend. As in the PID and fuzzy control, the adjustment of the water flow rates in secondary cooling is also done in the period which follows the unsteady casting speed. The model predictive control possesses an excellent control capability as the average surface temperature error is virtually constant with no subcooling and overheating. The value of the integral of the average surface temperature error is only 58 °C·s, cf. with values for other control approaches shown in **Table 1**. In conclusion, the model predictive control can be considered as the most effective control method among all the presented control algorithms.

5. CONCLUSION

The paper presents our developed advanced control algorithms for the optimal setup of secondary cooling in continuous steel casting, which are based on principles of fuzzy logic and model predictive control. The control systems integrate the dynamic solidification model of temperature field and solidification of cast strand. The cooling curves control algorithm and the PID regulation system were implemented in order to perform the analysis of control capabilities of the algorithms. Results show that our developed fuzzy regulator and the model predictive control system provide a great control of secondary cooling in a considered dynamic situation. The model predictive control showed the best control capabilities followed by the fuzzy regulator. On the other hand, the control by means of the cooling curve method provided rather poor results. Though the model predictive control system is quite computationally demanding, we used the massive parallelization on graphics processing units, which allowed for real-time computations.

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