MATHEMATICAL MODEL FOR STUDYING CONTROL OF SECONDARY COOLING IN CONTINUOUSLY CAST STEEL SLABS

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Abstract

To analyze secondary cooling control systems in continuous steel slab casting, a mathematical heat-transfer model and corresponding software tool were developed. The model is based on nonlinear heat conduction and solidification equations to predict temperature distribution in a longitudinal cross-section. The user interface accepts casting parameters such as mold heat flow and water flow rates in each spray zone, while enabling real-time temperature monitoring through charts and graphs. Results comparing temperature distributions under open-loop (spray table) and model-based predictive control systems are presented. This user-friendly modeling software serves as an effective tool for steelmakers and researchers to optimize secondary cooling in offline numerical experiments, to observe and monitor the process in real time, or to develop control systems to better maintain temperature during transients, for enhanced slab quality.

Keywords: Continuous casting, heat transfer, secondary cooling, control methods, numerical simulation

1. INTRODUCTION

Secondary cooling in continuous casting involves cooling the surface of the solidifying steel strand after it leaves the copper mold in the caster. In this stage, water sprays or air mist is applied at controlled flow rates to remove heat from the strand surface, which still contains a liquid core. In addition to promoting full solidification before the end of containment, controlled cooling should maintain good surface temperature distributions to avoid defects, even during transients.

Secondary cooling is dominated by internal heat conduction from the liquid within the slab to the surface, so the shell thickness grows in proportion with the square root of time. However, in thinner slabs, the spray cooling also has some effect on the shell growth and final solidification. More importantly, spray cooling of the surface controls the surface temperature history, which greatly affects defects and metallurgical quality [1] [2]. Surface cracks form if stress, such as caused by bending, unbending, or thermal stress, occurs when the surface temperature is in a range of low ductility, and depends greatly on the composition of the steel grade being cast [3]. Furthermore, excessive reheating of the strand surface can lead to internal cracks and shape defects [4]. Finally, if low secondary cooling and high casting speed combine to extend the metallurgical length beyond the region of roll support, then the serious, dangerous, and expensive defect of “whale formation” can occur due to excessive bulging caused by the internal ferrostatic pressure [5]. Secondary cooling is controlled by adjusting the water or air-mist flow rates in each spray-cooling zone (**Figure 1**), which can be adjusted independently in real time. Each adjustment of G_i affects the flow rate of every nozzle in the zone, and is made in response to current casting conditions, according to the desired temperature profile.

The flow rates should be carefully controlled to ensure that each part of the strand surface follows the desired thermal history for the grade, while considering the casting speed history. This task can be challenging, and requires a robust control strategy and methodology, which is the subject of ongoing research.

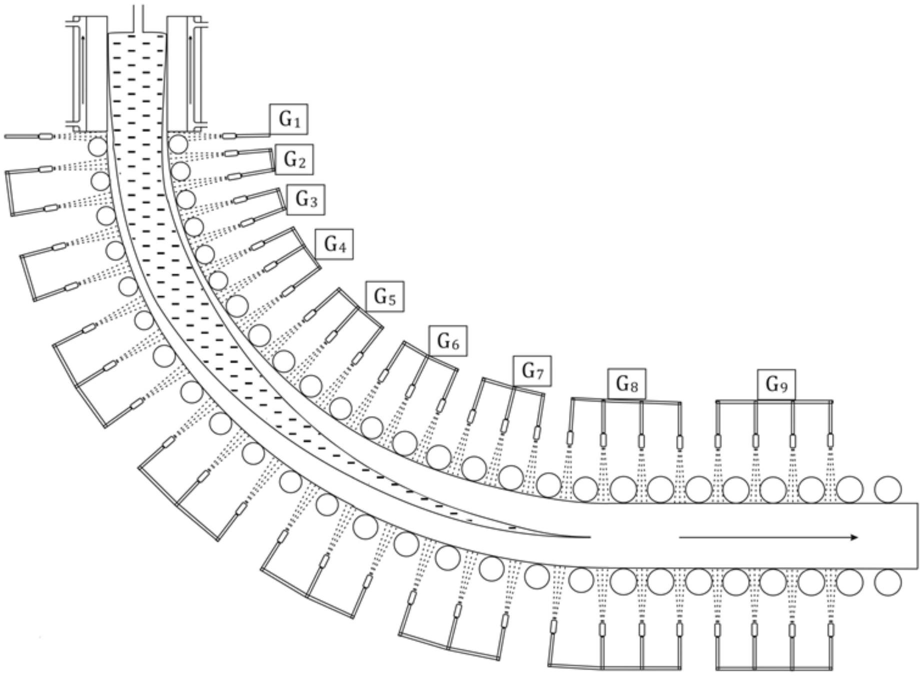

Figure 1 Schematic of caster showing secondary cooling spray zones and water-flow actuation points, G_i

During non-steady-state casting, some regions in secondary cooling may experience undesirable temperature transients if sprays are not controlled properly, potentially leading to strand defects or in extreme cases, even causing the strand to become stuck in the curved section of the casting machine [6]. Optimizing secondary cooling to best maintain slab surface temperatures is one control strategy. For example, as suggested in [7], maintaining the surface temperature above ~900 °C during straightening can be an effective measure to prevent transverse surface cracks in continuous-cast slabs. Many studies, such as [8] have confirmed this can be achieved by adjusting secondary cooling to keep the strand surface temperature above the low-ductility range of ~700–850 °C during straightening. Lowering water flow in certain cooling zones can also reduce transverse corner cracks and improve overall slab quality. Another strategy is to increase water flow rates in secondary cooling such that unbending occurs below the low-ductility temperature range.

Direct closed-loop control of spray cooling in continuous casting has been challenging due to unreliable sensors. Optical pyrometers are subject to changes in surface emissivity due to scale formation and the steamy environment of the spray chamber, and are difficult to maintain. Thus, traditional feedback control systems are not sufficiently robust for this process.

At the other extreme, a simple method to control secondary cooling is fully open-loop "spray table" control, where the flow rates are found by interpolation of values in a "look-up" table based on the casting speed. Although spray-table control is very robust and reliable, it produces variations in temperature history after sudden speed changes, as investigated later in this paper.

Recently, real-time adaptive (dynamic) cooling model-based control systems are being developed, often based on closed-loop feedback with a software sensor [5], or model predictive control systems [9] [10]. These systems provide strand temperatures in real time to the control system from a mathematical model, which acts as a "digital twin" of the caster. Such systems benefit from true real-time plant measurements of mold heat transfer, based on the cooling water heat up. They can be further improved by infrequent or periodic recalibration with pyrometer measurements, when such measurements are accurate and available. Other systems implement statistical evaluation of plant measurements [11], or augment a mathematical model or a historical database of temperature measurements and steel quality with a fuzzy logic regulator [12].

Dynamic spray cooling systems utilize mathematical models in two ways. Firstly, real-time heat transfer models can be integrated into the control system as software sensors. Such models can also serve as real-time observers of the process, providing knowledge to assist the operators [5, 10]. Secondly, offline mathematical models can aid in understanding the process and in the development of better control systems. This work shows results from a two-dimensional, transient model which can visualize the dynamics of the temperature field in a central longitudinal cross-section faster than in real time.

2. MATHEMATICAL MODEL

In this work, a transient mathematical model of convective-conductive heat transfer in a continuous steel strand [10] is applied to simulate the two-dimensional temperature field and solidified shell thickness evolution within a longitudinal section through the steel strand in a typical continuous slab caster. This section is parallel to the narrow faces and captures typical behavior between the wide faces, such as the caster centerline. To save on computation, the model domain includes only half of the strand thickness, assuming symmetry between the inside and outside radius.

This model solves the transient heat conduction equation for the two-dimensional temperature field, subject to convective-radiation boundary conditions, according to:

$$\frac{\partial T}{\partial \tau} + v(\tau) \cdot \frac{\partial T}{\partial z} = \frac{1}{c(T)\rho(T)} \left\{ \frac{\partial}{\partial x}\left[k(T)\frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial z}\left[k(T)\frac{\partial T}{\partial z} \right] \right\}, \qquad (1)$$

where T is the steel temperature, K; $v(\tau)$ is casting speed (m/min); $c(T)$ is specific heat capacity, J/(kg·K); $\rho(T)$ is density, kg/m^3; $k(T)$ is thermal conductivity, W/(m·K); t is time, sec; x is distance in the thickness direction, m; and z is distance in the casting direction, m. This equation is discretized with an explicit finite-difference numerical scheme. The position of the solidification front, defined by continuity of temperature across the phase boundary interface and by the Stefan condition, along with the handling of latent heat, initial conditions, boundary conditions, and other numerical details, are presented in [10].

The user interface displays casting parameters such as average and maximum heat flow in the mold, surface temperature, and water flow in each zone, while also allowing real-time temperature monitoring via charts and graphs. This model enables evaluation of different cooling strategies and their effects on shell temperature, thermal gradients, and crack susceptibility.

3. NUMERICAL EXPERIMENTS

Numerical experiments were conducted for a typical steel slab caster with 0.2 m slab thickness with standard casting speed of 1 m/min, and measured variations having a standard deviation of 0.028 m/min. The simulated scenario involves a realistic drop in casting speed during a ladle exchange (**Figure 2**).

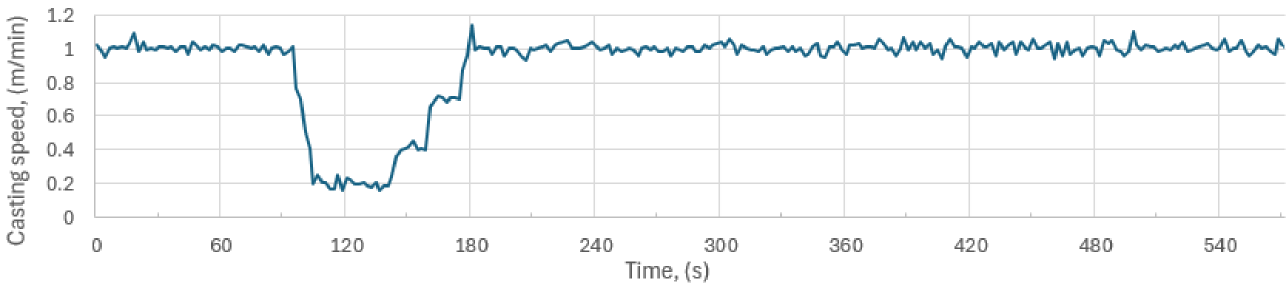

Figure 2 Casting speed data for experiments

The geometric parameters of the Continuous Casting Machine (CCM), including those of the secondary cooling zone, are taken from Slab Caster No. 6 at Azovstal. Thermophysical properties are taken from [13] for the steel whose chemical composition is presented in **Table 1**.

Table 1 Chemical composition of the steel (wt%)

C	Si	Mn	Ni	S	P	Cr	Cu
0,36…0,44	0,17…0,37	0,5…0,8	< 0,3	< 0,035	< 0,035	0,8…1,1	< 0,3

4. OPEN-LOOP (SPRAY-TABLE) CONTROL

The above scenario is first investigated with an open-loop spray-table control system. Open-loop control refers to a control system which does not consider plant measurements, or even model output data to determine the water flow rates at the actuation point of each spray zone. In this case, the algorithm is solely based on predefined rules based on the current casting speed. The values in the table are based on plant experience to produce temperature distributions which give good steel quality when running at constant, steady-state casting speed.

The particular spray-table control system implemented here features a linear relationship between the casting speed and the water flow rate. Any change in casting speed causes a directly proportional change in water flow rate (**Figure 3**). When operating at any constant casting speed, the prescribed flow rate maintains a constant specific water consumption per unit mass of steel. Suggested guidelines [14] are 1.0 to 1.2 L/kg of steel for plain-carbon and low-alloy steels; 0.6 to 0.8 L/kg for low-carbon and high-carbon steels; and 0.4 to 0.6 L/kg for steel grades with high sensitivity to thermal cracking. Water pressure is maintained between 0.1 and 0.5 MPa. Because each nozzle requires a minimum flow rate to produce a good spray pattern, according to its “turndown ratio“, water flow rates are constant at low casting speed (**Figure 3**). To compensate, some of the last secondary cooling zones may be completely turned off at low casting speeds. Open-loop spray-table control is easy to implement, very robust, and effective when operating under steady conditions.

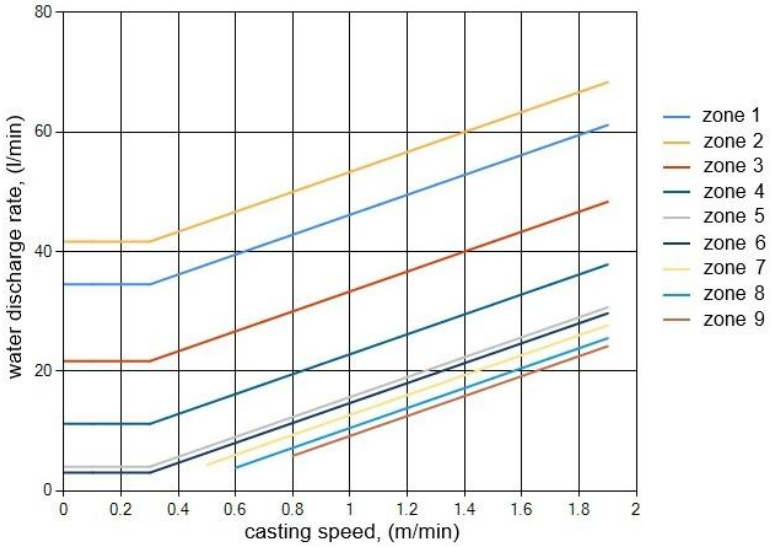

Figure 3 Water discharge rates for open-loop (spray table) control

The resulting water flow rates and temperature results are presented in **Figure 4a)**. For transient scenarios, such as this one, the temperature profiles deviate greatly from desired and vary between slices. The speed drop causes a flow-rate drop everywhere, including the later spray zones, where surface temperature rises. Steady state is not achieved again until all steel slices started during the speed drop have exited the last spray zone.

To improve this behavior, other open-loop algorithms have been developed which track the casting speed history of each slice of steel in the caster and adjust the water flows to implement a constant specific water consumption even during speed transients (e.g., [15]). The thermal behavior resulting from any of these algorithms can be analyzed and visualized using the software tool shown in this paper.

5. MODEL-BASED PREDICTIVE CONTROL

The other control system investigated here selects water flow rates which aim to maintain a constant surface “setpoint“ temperature history for each slice of steel during speed-change scenarios, based on temperature forecasts from a digital twin mathematical model [10]. This real-time dynamic model-based control system simulates temperature for several seconds into the future and finds, via iteration with interval halving, the water flow rates which maintain the setpoint temperature [16, 17]. Consequently, during a scenario with varying casting speed, the flow rate behavior varies greatly between spray zones, as shown in the upper frame of **Figure 4b)**. This is in stark contrast with the identical behavior with time in spray zones for spray-table control. The resulting temperatures show almost no deviation from the desired setpoints during the speed-drop scenario, as presented in **Figure 4b)**. The only deviations are observed in the first spray zone, where there is insufficient control authority, and where also the control algorithm is not perfect. Clearly, model-based dynamic spray-cooling control offers the potential for better control of spray cooling.

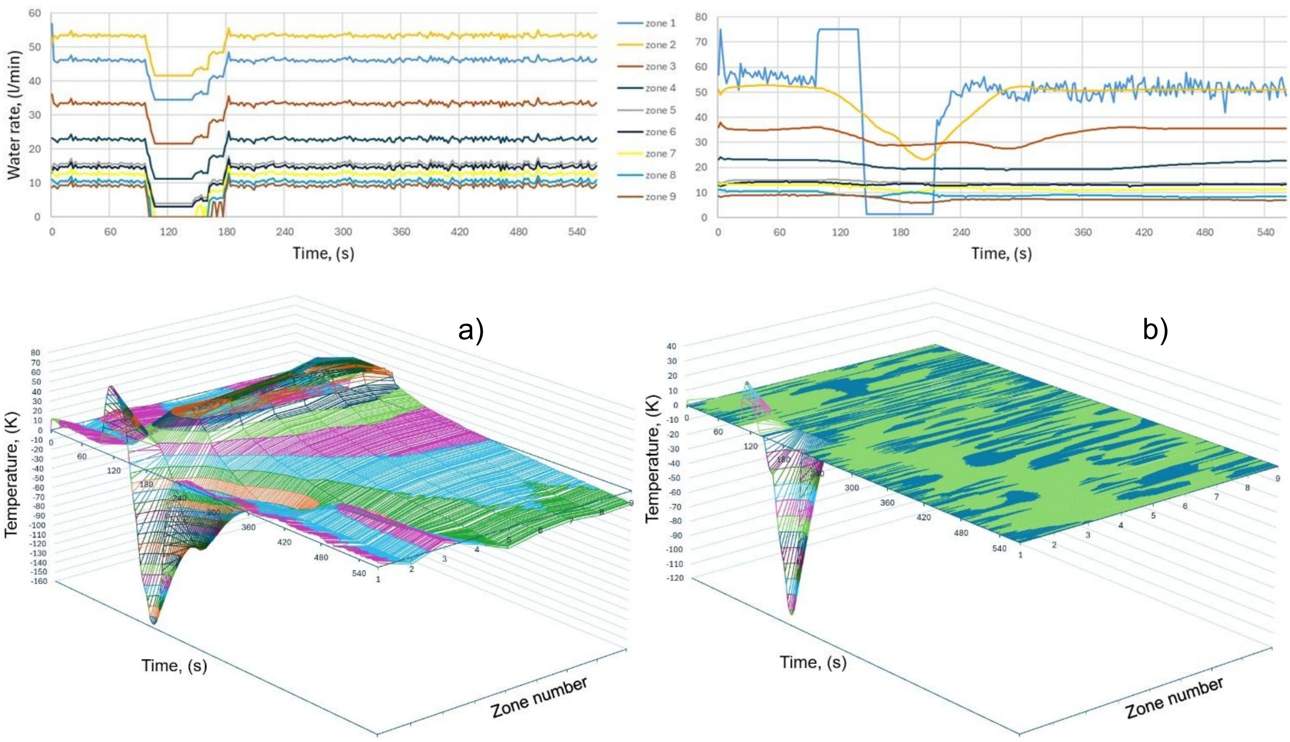

Figure 4 Water rates (top) and temperature deviations from the setpoint temperature (bottom).
a) Open-loop (spray-table) control method; b) Model predictive control method

6. CONCLUSION

A mathematical model and software tool of transient heat transfer and solidification is applied to visualize the behavior of two different control systems on water flow rates and the resulting temperature distributions produced during a speed-drop scenario encountered in a continuous steel-slab caster during a typical ladle exchange. The model system operates faster than real time, so is capable of serving as the model in a model-based control system at an operating caster. The output screens can support operators to visualize the thermal behavior of their process in real time. The software tool can also be applied to evaluate the behavior of different spray-cooling control systems. These include open-loop spray-table control and model-predictive cooling control strategies, shown in this work. This software tool offers valuable support for both researchers and steelmakers to understand and improve slab quality through better control of secondary cooling processes.

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