1. Introduction

The continuous casting process is the predominant method for the solidification of molten steel into semi-finished shapes such as blooms, billets and slabs.

For the past ten years, the reigning control problem in continuous casting has been mould level oscillations. It has been proven extensively that variations in the level of the mould cause depressed regions filled with mould flux which lead to surface defects. Many authors have dealt with this problem by applying mould level control.

Another approach which could lead to the improvement of strand surface and interior quality is the application of control to the spray zones in the secondary cooling zone (SCZ). Due to reheating and improper cooling profiles in the secondary cooling zone, surface and internal cracks form; these cracks adversely affect the quality of the steel. Reheating is primarily caused by improper spray pattern designs in the secondary cooling zone. Furthermore, changes in casting speed cause strand temperatures to deviate from the designed temperatures, causing even further reheating between spray zones. Other problems associated with the secondary cooling zone are the clogging of sprays due to scale or calcification, and the effect that rollers have on the strand surface temperature.

This paper presents an alternate way to apply speed disturbance rejection in the secondary cooling zone. A brief overview of the continuous casting process is presented after which a dynamic model of the strand temperature is described. The use of feedforward control is then discussed. A feedforward control scheme is required because, in general, temperature measurements are not feasible due to scale and steam affecting the optical pyrometer measurements in the secondary cooling zone.

2. Process Overview

The continuous casting process found in most steel
plants in the world is of the bow caster type (see Fig. 1).

The ladle arrives at the caster containing liquid steel at a temperature well above the liquidus temperature. The ladle feeds the tundish which acts as a reservoir of molten steel. The tundish controls the flow of steel into the mould through some mechanism such as a stopper rod. The primary extraction of heat from the strand takes place in the mould. Below the mould, the secondary cooling zone removes most of the heat from the strand through water sprays. The water sprays are grouped into 3 to 6 zones, with each zone independently controlled through valves to regulate the flow of water to the sprays. The secondary cooling zone is typically 6 metres long for billet casters. The strand is supported by rollers and movement of the strand is effected by extraction rollers. Below the secondary cooling zone, the strand cools off naturally in the radiation zone. After the radiation zone, the strand is cut into specified lengths and sent for further processing.

3. Approach

The approach taken is to first of all derive a dynamic model describing heat transfer in the continuous casting process. The model is dynamic in the sense that it calculates changes in strand temperatures with time, in response to changes in casting speed and spray water flow rate. The dynamic model can be simplified to obtain a steady state model.

Since temperature is generally not measured along the secondary cooling zone, plant input/output data is not available to
1. validate the dynamic model accurately,
2. apply system identification* to obtain a model from plant experiments,
3. apply direct output feedback control.

For these reasons, the dynamic model is used to represent the actual plant for controller design purposes, and input/output (I/O) data is generated from the dynamic model for system identification.

In this model, the inputs are the heat transfer coefficients in the secondary cooling zones. These heat transfer coefficients (which are set by manipulating the water flux) describe the boundary conditions for calculating the temperatures with the dynamic model. The model yields the temperature distribution throughout the strand as a function of time, but the midface temperatures at the end of each spray zone were chosen as the outputs to be controlled. These were chosen because the effect of a changing boundary condition is the largest at the end of the cooling zone.

For control of these temperatures, changes in casting speed is viewed as a “disturbance” which tends to change the strand temperature if it should assume a new value. Changes in the heat transfer coefficients in the spray zones are used as the manipulated variables which are used to keep the strand temperatures close to the required values. The effects of heat transfer coefficients and casting speed are determined by using the dynamic model.

For controller design, system identification is applied to the model results to derive LTI (linear time invariant) transfer functions which describe the effects of changes in casting speed and heat transfer coefficients. This approach serves as a “linearisation” of the system which facilitates controller design. Due to the lack of temperature measurement, direct testing of the efficacy of a controller is difficult in practice. For this reason, the controllers are tested on the full discrete non-linear dynamic model which acts as a substitute for the real casting process.

4. Dynamic Model

The dynamic model which describes heat transfer in the secondary cooling zone in continuous casting is derived by using an energy and mass balance on the strand. The partial differential equation that describes this process is given by

\[
\frac{\partial H}{\partial t} + v \frac{\partial H}{\partial z} + \rho \frac{\partial v}{\partial t} = K \nabla^2 T + a T \cdot \nabla T \quad \text{(1)}
\]

The density \(\rho = \rho(T)\) is a function of temperature. \(T = T(x, y, z, t)\) is the temperature distribution in the strand as a function of time. \((x, y)\) are the transversal coordinates, while \(z\) is the axial coordinate along the strand and \(t\) is the time evolution of the system. \(H = H(x, y, z, t)\) is the enthalpy. The thermal conductivity \(K = K(T)\) is a strong function of temperature; it is assumed that the temperature dependence is linear \(i.e., K = aT + b\). The speed \(v = v(t)\) is independent of the distance along the axial direction \(i.e., v\) the strand cannot stretch. \(V = e_x \cdot \frac{\partial}{\partial x} + e_y \cdot \frac{\partial}{\partial y}\) is the del operator. It is assumed that heat transfer by conduction in the axial direction is negligible compared with the energy transfer in the axial direction by strand movement.

The relation between enthalpy and temperature is given by

\[
H(T) = \int_0^T \rho(\tau) \left( c(T) - L_n \frac{\partial f}{\partial \tau} \right) d\tau \quad \text{(2)}
\]

\(L_n\) is the latent heat of solidification of the steel; \(c(T)\) is the heat capacity. The fraction solidified (denoted by \(f_\tau\)) is assumed to increase linearly from the liquidus to the solidus temperature; hence \(f_\tau\) is related to the solidus \((T_s)\) and liquidus \((T_L)\) temperatures through \(\partial f/\partial T = -1/(T_L - T_s)\), \(\forall T_s > T_0\). The boundary conditions constitute the casting speed in the mould, the rate of heat extraction in the mould, and the heat transfer coefficient fixed by the sprays and rollers in the secondary cooling zone and the radiation zone.

The model obtained is difficult to solve analytically; so a numerical differencing scheme is used to approximate the partial differential equation. For this implementation, an explicit finite difference scheme in both time and space was used to solve the system. Similarly, the steady state model can be derived from Eq. (1) by letting all partial time derivatives equal zero and noting that, at steady state, \(z = v, v = \text{constant}\). Some values required in the computation of the example model are given in Table 1.

* System identification refers to empirical determination of the sensitivity of the strand temperature to changes in casting speed and water flux, and the time delays and response times of the reaction of the temperature to such changes.

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The thermal conductivity– and enthalpy–temperature relations of the example model are given in Fig. 2. These values—which correspond to low-carbon steel—were those used in previous finite-difference calculations on continuous casters. It will be noted in Table 1 that an erroneously high value (1554°C) was used for the liquidus temperature (the liquidus temperature of low-carbon steel is expected to be close to that of pure iron at 1538°C). This 16°C error was found not to affect the simulations noticeably, however, since the concern here was with the surface temperature of the strand.

5. Open-loop Control

Some reference condition (of casting speed and spray zone settings) is required as the starting point for the system identification exercise. The conditions in Table 1 were assumed. The heat transfer coefficients were found by means of a performance index:

\[ J(h_{\text{ref}}) = \int_0^L L(T_{\text{ref}}, h_{\text{ref}}) \, dz \] ..............(3)

In Eq. (3) \( h_{\text{ref}} \in \mathbb{R}^n \) are the inputs (heat transfer coefficients) and \( T_{\text{ref}} \in \mathbb{R}^m \) is the output (calculated temperature at the end of each spray zone). The Lagrangian \( L \) is the quadratic penalty function which contains
1. The metallurgical specification of required temperatures along the axial \( z \) direction in terms of temperature.
2. Bounds on the maximum allowable reheating along the axial direction.
3. Limits on the heat transfer coefficients \( h_{\text{ref}} \) in each of the spray zones.

\( z_2 - z_1 \geq 0 \) is the distance from the end of the mould to the end of the secondary cooling zone. The penalty function can be minimised using any reliable minimisation algorithm and the steady state model. An example of the result of the minimisation is given in Fig. 3. Note in this figure that \( z = 0 \) corresponds to the meniscus level. The mould exit temperature and shell thickness were calculated by assuming the average heat flux in the mould to be \( 1.2 \times 10^6 \text{ W/m}^2 \), the heat flux at the midface of the mould exit to be \( 1.0 \times 10^6 \text{ W/m}^2 \), and the heat flux at the mould corners to be \( 0.5 \times 10^6 \text{ W/m}^2 \). These values were based on literature values.

The caster has five distinct spray zones. In this case, the cooling specification is such that it is required for the strand midface to cool linearly from the end of the mould to the end of the secondary cooling zone, by 150 degrees Centigrade. This is indicated by the broken line (cooling specification) running through the solid line (minimisation result) in the figure. Reheating of up to 50 degrees is allowed. This is depicted in Fig. 3 by the bounds (broken lines) of \( \pm 25^\circ \text{C} \) on either side of the cooling specification. The near-ideal solution achieved by the minimisation algorithm for this case is the solid line in Fig. 3. The result is that the heat transfer coefficient vector has the following values:

\[ h_{\text{ref}} = [525 \ 409 \ 360 \ 307 \ 278]^T \text{ W/m}^2 \text{ °C} \] .........(4)
6. Linearised Model

After discretisation of the dynamic model, obtaining input/output data, and system identification, the linearised model is described by the following equation in the Laplace domain:

\[ G_p(s)\Delta h(s) + g_i(s)\Delta T(s) = \Delta T(s) \] ..........................(5)

where \( \Delta h(s) = [\Delta h_1(s) \Delta h_2(s) \cdots \Delta h_n(s)]^T \) are the manipulated variables (heat transfer coefficients in each zone) and \( \Delta T(s) = [\Delta T_1(s) \Delta T_2(s) \cdots \Delta T_n(s)]^T \) are the outputs (mid-surface temperature at the end of each zone). There are \( n \) distinct spray zones. \( \Delta T(s) \) is the speed disturbance. The variables \( \Delta h, \Delta T, \) and \( \Delta v \) are all deviations from the reference values*. The “plant” transfer function, \( G_p(s) \), relates the heat transfer coefficients to temperature; and the disturbance transfer function, \( g_i(s) \), relates the speed disturbance to temperature. Figure 4 is a block diagram depiction of the system.

6.1. Plant Transfer Function (Changes in Heat Transfer Coefficients)

The plant transfer function was found to have the following lower triangular structure (refer to the Appendix):

\[
G_p(s) = \begin{bmatrix}
g_{i1}(s) & 0 & 0 & \cdots & 0 \\
g_{i2}(s) & g_{i2}(s) & 0 & \cdots & 0 \\
g_{i3}(s) & g_{i3}(s) & g_{i3}(s) & \cdots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
g_{in}(s) & g_{in}(s) & g_{in}(s) & \cdots & g_{in}(s)
\end{bmatrix} \] ..........................(6)

where the \( g_{ij}(s) \in \mathbb{R} \), \( \forall i=1,2,\cdots, n, j\leq i \) are LTI transfer functions with the following structure:

\[
g_{ij}(s) = \begin{cases} 
\frac{k_i}{\tau_i \cdot s + 1} & \forall i = j \\
\frac{k_i e^{-\alpha_i t}}{\tau_i \cdot s + 1} & \forall i < j
\end{cases} \] ..........................(7)

* e.g. \( T_i(t) = T_{ref} + \Delta T(t) \) is the actual temperature where \( T_{ref} \) is the nominal “ideal” designed temperature and \( \Delta T \) is the deviation from \( T_{ref} \).

The structure of the plant transfer function is lower triangular because a change in heat transfer coefficient in one zone can only have an effect on temperature in that, and subsequent zones, and cannot affect preceding zones. This is due to the facts that the strand moves in one direction only, and that the heat transfer in the axial (z) direction is negligible. In Eq. (7) the \( k_i \in \mathbb{R}, \forall j \leq i \) are the steady state gains of the system, and the \( \tau_i \in \mathbb{R}, \forall j \leq i \) are the time constants of the transfer functions. The unit of \( \tau_i \) is seconds and \( k_i \) is \( \text{W} \cdot \text{m}^{-2} \cdot \circ \text{C}^{-1} \).

Due to a heat transfer coefficient change in zone \( j \) only acting in on zone \( i \) (\( i \neq j \)) after some period of time, the \( e^{-\alpha_i t} \) term is included to represent the transport delay in all transfer functions below the main diagonal of \( G_p(s) \). These effects are illustrated by the actual input/output data in Figure 5.

The rows represent step decreases in heat transfer coefficients of \(-100 \text{ W} \cdot \text{m}^{-2} \cdot \circ \text{C}^{-1}\) in each spray zone and columns represent the resulting temperature response as a function of time in each spray zone. For example, the first row gives the temperature changes in the five zones if the heat transfer coefficient in the first zone is decreased. The immediate response in the first zone is evident, as are the time delays and smaller effects for temperature changes in the subsequent zones.

The transport delay is a function of the casting speed and the distance between zone \( j \) and zone \( i \) (\( l_j \)):

\[
\theta_j = \frac{l_j}{v} \] ..........................(8)

The values for the coefficients are strong functions of temperature, shell thickness and spray zone length.\(^{50}\) The value of \( \tau_{ij} \), for example, changes as a function of the average shell thickness and thermal diffusivity in zones \( j \) to \( i \), i.e.

\[
\tau_{ij} = \frac{r^2}{\alpha_j} \quad \alpha_j = \frac{K_j}{
\end{bmatrix} \rho_{ij} c_{ij}} \] ..........................(9)

\[ T_{ref} \] is the nominal “ideal” designed temperature.
where \( r_j \) is the average shell thickness from zone \( j \) to zone \( i \). Because of this effect, the time constant is larger further down the strand, in line with the expected larger shell thickness. This is best seen by comparing the traces along the diagonal in Fig. 5 (i.e. temperature changes in a zone due to a decrease in heat transfer coefficient in that zone). \( \alpha_j \) is the average thermal diffusivity\(^{11} \) between zones \( j \) and \( i \) of the shell. \( K_p, p_i \) and \( c_j \) are the average thermal conductivity, density and specific heat between zones \( j \) and \( i \), respectively.

### 6.2. Disturbance Transfer Function (Speed Changes)

The disturbance transfer function was found to have the following structure

\[
g_d(s) = \begin{bmatrix} d_1(s) \\ d_2(s) \\ \vdots \\ d_n(s) \end{bmatrix}
\]

where the \( d_i(s) \in \mathbb{R}(s), i=1, 2, \ldots, n \) are transfer functions relating the speed disturbance to each of the output temperatures. A second-order function for \( d_i(s) \) was found to fit the response adequately and is almost critically damped (\( \zeta_i=0.7, \forall i; \) refer to the appendix) i.e.

\[
d_i(s) = \frac{k_i}{(s/\omega_n)^2 + 2\zeta_i s/\omega_n + 1}, \quad \forall i=1, 2, \ldots, n
\]

The natural frequency (\( \omega_n \) in rad/s) and gain \( k_i \) (in °C/s/m) are strong functions of the applied speed change.\(^8 \) The gains vary very little between spray zones, but the natural frequency of the different spray zones depends strongly on the length of the spray zones (the full effect of a speed change takes longer to be felt in the furthest spray zone).\(^9 \) Figure 6 shows the SID data when a speed change of \( \Delta v = -0.25 \) m/min was applied to the system.

#### 7. Controller

The standard controller used in practice measures the speed disturbance and applies a change to all the valves through a master valve. The design for this type of system can be approached as follows.

##### 7.1. Group Valve Control

A typical feedforward speed disturbance compensator found in practice relies on measurement of the speed disturbance and then manipulates the master spray valve to effect an absolute temperature deviation reduction. Such a controller can be designed using the following procedure. When assuming that a linear change in the master valve causes a linear proportional change in all spray valves, the control loop is described by (see Fig. 7).

\[
G_p(s)g_c + g_d(s) = \Delta T(s) \Delta r(s)^{-1} \quad \text{..............(12)}
\]

where \( i=1 \ 1 \ \cdots \ 1 \) \( \in \mathbb{R}^n \) and \( g_c \in \mathbb{R} \) is the (scalar) controller. Since it is required to have no deviation in temperature, \( \Delta T \) is set to the zero vector to determine \( g_c \), e.g.

\[
G_p(s)g_c + g_d(s) = 0 \quad \text{..................(13)}
\]

The above equation results in \( n \) equations with one unknown: \( g_c \). This means that the controller cannot ensure total disturbance rejection even if the model of the plant is extremely accurate. To determine \( g_c \), a weighted pseudoinverse\(^{20} \) is used. The weighting matrix is chosen such that the longer spray zones are more important because they have a great effect on the temperature change. Equation (13) then becomes

\[
WG_p(s)g_c = -Wg_d(s)
\]

\[
(\mathbf{W}g_p(s)i)H \mathbf{W}G_p(s)g_c = -((\mathbf{W}g_p(s)i)H\mathbf{W}g_d(s)) \quad \text{..................(14)}
\]

The hats (\( \hat{\cdot} \)) indicate that the derived version of the plant from the non-linear model is used, and the superscript \( H \) indicates the Hermitian of the vector. \( \mathbf{W} \in \mathbb{R}^{n \times n} \) is the weighting matrix with all off diagonal elements equal to zero. The controller, \( g_c \), is a constant. For this reason an appropriate frequency has to be chosen at which the plant dynamics are cancelled. Since steady state behaviour should ensure that almost no steady state error results, the controller is designed such that plant dynamics are cancelled at steady state. Such a controller results from the following control law.

**Control Law 7.1. Constant controller at steady state.**

*From Eq. (14) the controller is*
The frequency response of the new disturbance transfer function, defined by substitution of Eq. (15) in Eq. (12), is depicted in Fig. 8. In this figure, as in Fig. 9 and Fig. 13, the x-axis denotes the frequency of the speed change. A wide range of frequencies is shown, since actual speed changes by steps or ramps can be considered to be the result of a combination of changes at different frequencies (as quantified by the Fourier transform of such a speed change).

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The improvement with the adaption of the controller is marginal compared to the uncontrolled case (see Fig. 9), so that, even at steady state, the controller will not perform. This can be seen from the high gain at low frequency in Fig. 9. The time response of the system is given in Fig. 11, with a speed input as in Fig. 10.

The overshoot in temperature following the speed change is the result of the immediate change in water flow as soon as the speed change occurs. This means that the corrective action is applied well before the full effect of the speed change is felt (Fig. 6 gives an indication of the response times), resulting in over-compensation in the short term.

The figure clearly indicates the effect of the weighting matrix since the longer zones have less steady state error than the shorter zones. The effect of plant non-linearities can also be seen from the temperature response in zone III, where a steady state error persists when casting at nominal speed.

In this case, the weighting matrix is given by $W = \text{diag}(\mathbf{w})$ where

$$\mathbf{w} = [0.0859 \ 0.0859 \ 0.1227 \ 0.3374 \ 0.3681]^T$$
Fig. 12. New structure of the system with controller $g_c(s)$.

and the matrices $\hat{G}_p(s)$ and $\hat{g}_d(s)$ can be found in the appendix. The resulting controller is $g_c = 170.1$.

7.2. Improved Controller

A substantial improvement over the controller in Sec. 7.1. can be made if two assumptions are made:
1. The spray valve in each zone can be individually manipulated, and
2. the feedforward control system can include dynamic control.

The improvement can be achieved when the plant transfer function (Eq. (6)) is dynamically inverted along the main diagonal, while the rest of the transfer function is inverted at steady state. This strategy is used because the main diagonal elements have the greatest influence on the system. Furthermore, the non-diagonal elements contribute very little in terms of bandwidth and therefore one can readily assume that the main dynamic behaviour is caused by the main diagonal. By deploying such a controller, some of the dynamics of the system are easily incorporated into the controller, thus ensuring a better response to speed disturbances. The new dynamic controller $g_c(s)$ is a vector shown in Fig. 12.

The controller is defined by the following control law.

**Control Law 7.2.** Dynamic inversion of $\hat{G}_p(s)$ along the main diagonal.

To dynamically invert the plant transfer function along the main diagonal, while inverting the rest of the plant at steady state; the following control law can be used:

$$g_c(s) = -(\lim_{s \to 0} [\hat{G}_p^{-1}(s)] - \Sigma [\hat{G}_p^{-1}(s)])\hat{g}_d(s)$$

$$= -(\lim_{s \to 0} [\hat{G}_p^{-1}(s)] - \lim_{s \to 0} (\Sigma [\hat{G}_p^{-1}(s)])\hat{g}_d(s)$$

$$= -(\lim_{s \to 0} [\hat{G}_p^{-1}(s)] - \lim_{s \to 0} (\Sigma [\hat{G}_p^{-1}(s)])\hat{g}_d(s)$$

$$= -(\lim_{s \to 0} [\hat{G}_p^{-1}(s)] - \lim_{s \to 0} (\Sigma [\hat{G}_p^{-1}(s)]))\hat{g}_d(s)$$

$$= -(\lim_{s \to 0} [\hat{G}_p^{-1}(s)] - \lim_{s \to 0} (\Sigma [\hat{G}_p^{-1}(s)]))\hat{g}_d(s)$$

$$= -(\Sigma [\hat{G}_p^{-1}(s)] - \lim_{s \to 0} (\Sigma [\hat{G}_p^{-1}(s)]))\hat{g}_d(s)$$

$$= -(\Sigma [\hat{G}_p^{-1}(s)] - \lim_{s \to 0} (\Sigma [\hat{G}_p^{-1}(s)]))\hat{g}_d(s)$$

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$$= -(\Sigma [\hat{G}_p^{-1}(s)] - \lim_{s \to 0} (\Sigma [\hat{G}_p^{-1}(s)]))\hat{g}_d(s)$$

where $\Sigma (\cdot)$ is a diagonal matrix with the same dimension as $(\cdot)$.

The transfer function in control law 7.2 is improper along the main diagonal for this application (inversion of a first order transfer function). For this reason, to be able to implement the controller on a personal computer, fast poles are added along the main diagonal of the controller to make it biproper. These poles can be chosen to be fast enough to fall outside the bandwidth region of the plant, but care should be taken when taking the sampling rate into consideration. A too high bandwidth may be in direct violation of the Nyquist sampling theorem. In the “implementation” of this controller a sampling interval of 0.1 s was chosen which is the same as the time step size in the dynamic “plant”. The smallest time constant in the whole process is about 4 s, so that a sampling interval of $T_s = 4/10 = 0.4$ s should suffice. The choice of the sampling interval was purely to simplify the controller implementation process, so that no extra registers or counters were required to store previous values for the controllers.

The fast poles of the controller should not be too large so that the sampling theorem is not satisfied, and the poles should not be too slow so that they influence the actual
transfer of the plant. Therefore, the poles of the controller are chosen as the geometric mean between the sampling period and the zero in the controller: \( p_i = \sqrt{z_i T_s}, \forall i = 1, 2, \cdots, n \), where \( p_i \) are the poles and \( z_i \) the zeros of the controller and \( T_s \) is the sampling time of the system.

The result of such a controller implementation is shown in Fig. 13 and the controller is given in the appendix.

As can be seen from Fig. 13, speed disturbance rejection has improved by 20dB over the controller in Fig. 8. Also, steady state offsets are minimal compared to that of the constant controller. The time simulation is shown in Fig. 14.

A speed change of \( \Delta v = -0.5 \text{ m/min} \) was implemented at \( t = 0 \) s and at \( t = 300 \) s the speed was reverted back to \( v_{ref} = 2 \text{ m/min} \) (nominal casting speed). This graph shows that the temperature deviations have improved so that the maximum variation from the “ideal” temperature distribution is about eighteen degrees Centigrade. The controller in Eq. (15) which can be used for current industrial purposes is weak and the enhanced controller of Eq. (17) can be used as an alternative.

8. Practical Issues

Some practical issues have to be addressed. Throughout this paper the heat transfer coefficients are used as the inputs. This is widely accepted in literature, but the actual input is an electric signal. The electric signal drives a valve which regulates the displacement of the valve. The displacement causes a water flow rate which again is related to the heat transfer coefficient and is highly dependent on the nozzle type and arrangement.

The use of feedback control for the implementation in practice is not feasible since temperature is generally not measured in the secondary cooling zone. This also makes it hard to validate any model used to study heat transfer in the continuous casting process.

Furthermore, the model is dependent on the size of the applied speed change. This non-linear relation restricts the range of the model so that the controllers can only be used in a small linear region.

9. Conclusion

In this article, an alternate approach to speed disturbance rejection in the secondary cooling zone of a steel billet continuous caster was proposed. A process description was given, the dynamic model described and the open-loop formulation given. The general approach to the control of the secondary cooling zone in continuous casting was then given for cases where temperature measurements are not possible. A design methodology for the standard controller used in practice was then shown, and potential improvement over such a controller was described. In future, several aspects can be addressed to improve quality of casting products. This could include the development of soft sensors which accurately infer the temperatures in the secondary cooling zone.

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Appendix

\[ \hat{g}_p(s) = \begin{bmatrix} \frac{0.3137}{4.2s+1} & 0 & 0 & 0 & 0 \\ \frac{0.0743e^{-4.154}}{5.4s+1} & \frac{0.3292}{4.7s+1} & 0 & 0 & 0 \\ \frac{0.0313e^{-4.124}}{7.1s+1} & \frac{0.0616e^{-4.130}}{7.9s+1} & \frac{0.3686}{6.4s+1} & 0 & 0 \\ \frac{0.0126e^{-23.1}}{2.3s+1} & \frac{0.0193e^{-23.7}}{8.4s+1} & \frac{0.0449e^{-48.5}}{16.5s+1} & \frac{0.5023}{14.3s+1} & 0 \\ 0 & 0 & 0 & \frac{0.0893e^{-446.6}}{20.2s+1} & \frac{0.5165}{16.2s+1} \end{bmatrix} \]

\[ \hat{g}_d(s) = \begin{bmatrix} 100 \\ \frac{260s^2+24s+1}{87} \\ \frac{590s^2+33s+1}{93} \\ \frac{977s^2+46s+1}{100} \\ \frac{3606s^2+79s+1}{100} \\ \frac{4394s^2+98s+1}{100} \end{bmatrix} \]

\[ g_1(s) = \begin{bmatrix} \frac{4.2s+1}{0.3137(1.3s+1)} & 0 & 0 & 0 & 0 \\ \frac{0.0743^{-1}}{4.7s+1} & \frac{0.3292(1.37s+1)}{0.392} & 0 & 0 & 0 \\ \frac{0.0313^{-1}}{6.4s+1} & \frac{0.0616^{-1}}{0.3686(1.6s+1)} & 0 & 0 & 0 \\ \frac{0.0126^{-1}}{14.3s+1} & \frac{0.0193^{-1}}{0.0449^{-1}} & \frac{0.5023(2.4s+1)}{0.5165(2.5s+1)} & 0 & 0 \\ 0 & 0 & 0 & \frac{0.0893^{-1}}{16.2s+1} & \frac{0.5165(2.5s+1)}{16.2s+1} \end{bmatrix} \]

\[ g_2(s) = \begin{bmatrix} \frac{4.2s+1}{0.3137(1.3s+1)} & 0 & 0 & 0 & 0 \\ \frac{0.0743^{-1}}{4.7s+1} & \frac{0.3292(1.37s+1)}{0.392} & 0 & 0 & 0 \\ \frac{0.0313^{-1}}{6.4s+1} & \frac{0.0616^{-1}}{0.3686(1.6s+1)} & 0 & 0 & 0 \\ \frac{0.0126^{-1}}{14.3s+1} & \frac{0.0193^{-1}}{0.0449^{-1}} & \frac{0.5023(2.4s+1)}{0.5165(2.5s+1)} & 0 & 0 \\ 0 & 0 & 0 & \frac{0.0893^{-1}}{16.2s+1} & \frac{0.5165(2.5s+1)}{16.2s+1} \end{bmatrix} \]