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Dynamic spray cooling control model based on the tracking of velocity and superheat for the continuous casting steel

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ABSTRACT

An open-loop dynamic spray cooling control strategy is explained in details. The strand was divided into many slices of a certain length and the midpoint of each cooling zone was set as a control point. The casting speed and temperature of each slice were tracked by using a control algorithm. Compared with the steady-state control model, the maximum temperature fluctuation values of cooling zone I–IV dropped from 70 °C, 61 °C, 51 °C and 35 °C to 17 °C, 16 °C, 12 °C and 10 °C, respectively, when using the dynamic control strategy in theoretical case. This dynamic control strategy has been applied to an actual billet continuous casting machine. The results of field trials showed that the surface temperature of the billets was well stabilized at the target temperature, and the number of strand defects, such as mid-way cracks, was reduced significantly.

1. Introduction

The continuous casting process is essentially one of continuous heat withdrawal and solidification. During this process the liquid steel is first poured into a copper mold (open ended), and the mold is then cooled with cooling water, and the first solidification takes place at the metal-mold interface. After that the strand enters the secondary cooling zone (SCZ), and is further cooled by being sprayed with water, by contacting with water-cooled support (and driven) rolls, and also by radiation. About 80% of the heat is extracted in the secondary cooling process, at which point the liquid steel is completely solidified. The secondary cooling control technology thus determines the productivity of the caster, and also has significant effects on the quality of the strand.

The secondary cooling control method used to be manual control, which depended greatly on the experience and skill of the operator, and thus this approach was often unable to produce strands of necessary quality. However, nowadays, nearly all secondary cooling processes are under automatic control, and can be divided into two classes, as follows: (1) Closed-loop control. For instance, Long et al. (2011) developed a closed feedback loop control method for online secondary cooling control, in which the control input was the measured temperature signal, typically obtained with an infrared or CCD pyrometer sensor, and the output was the water volume adjustment signal (the so-called SISO: single-input single-output), based on a comparison between the actual measured temperature and target temperature. Spitzer (1992) proposed a real-time model-based systems which used the temperature measured at 4 or 5 set points as the feedback signal, and then calculated the real-time water flow using a heat-transfer model as the output signal. The accuracy and reliability of temperature measurements are thus very important for closed-loop control methods. Unfortunately, the very poor measuring environment in this context, due to the factors such as dust, water mist, water vapor and oxide scale on the strand surface, makes the measurements of pyrometer sensor inaccurate. Therefore, no accurate temperature data is available to adjust the water flux of the cooling sprays in the feedback configuration. (2) Open-loop control, uses only the water volume adjustment signal as the output signal, which is obtained

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Nomenclature

a, b, c	Parameters
C_P	Specific heat, kJ kg^{-1} °C^{-1}
$C_{p,\mathrm{eff}}$	Effective specific heat, kJ kg^{-1} °C^{-1}
D_i	Compensation coefficients of the superheat of the ith cooling zone, L min^{-1} °C^{-1}
f_{sol}	Solidification fraction
F	Compensation coefficients of cooling water temperature of the ith cooling zone, L min^{-1} °C^{-1}
h_s	Heat-transfer coefficient, kW m^{-2} °C
ΔH	Solidification latent heat, kJ kg^{-1}
k_i	Partition coefficient
L	Distensice from meniscus, m
L_i	Distance from meniscus of control point of the ith cooling zone, m
L_s	Cooling region length, m
N	Sample number
Q_i	Total water flow rate of the ith cooling zone, L min^{-1}
$Q_{b,i}$	Base water flow rate of the ith cooling zone, L min^{-1}
$Q_{i,\mathrm{lim}}$	Critical water flux of the ith cooling zone, L min^{-1}
$Q_{s,i}$	Superheat compensation water flux of the ith cooling zone, L min^{-1}
$Q_{w,i}$	Water temperature compensation water flux of the ith cooling zone, L min^{-1}
s	Strand girth, m
T	Temperature, °C
T_0	Best superheat, °C
T_{am}	Ambient temperature, °C
T_c	Casting temperature of steel, °C
T_{liq}	Liquid temperature of steel, °C
T_s	Actual superheat of liquid steel, °C
T_{sol}	Solidus temperature of steel, °C
T_{sur}	Surface temperature of strand, °C
T_{tt}	Target surface temperature, °C
T_w	Cooling water temperature, °C
$T_{w,0}$	Optimized cooling water temperature, °C
V_c	Casting speed, m min^{-1}
V_{lim}	Critical casting speed, m min^{-1}
$V_{m,i}$	Modified effective speed, m min^{-1}
W	Water flux, L m^{-2} s
$W_{w,0}$	Water flux on the temperature $T_{w,0}$
α	Machine constant
δ	Stefan–Boltzmann constant (5.67 × 10^{-8}), W m^{-2} °C $^{-4}$
ϵ	Strand emissivity
λ	Thermal conductivity, W m^{-1} °C^{-1}
λ_{eff}	Effective thermal conductivity, W m^{-1} °C^{-1}
ρ	Density, kg m $^{-3}$
σ	Standard deviation, °C
τ	Time, s

based on the preset water table or real-time calculations. The simplest secondary cooling automatic control method is known as the speed-tie approach, in which the zone flow is specified as a water table using flow-versus-speed. Another kind of open-loop control methods use real-time calculations of the surface temperature of the strand at very short time intervals as input signal, and these are obtained according to the heat-transfer and solidification model. For example, Louhenkilpi et al. (1993) developed a control model called DYNCOOL based on a real-time model. Hardin et al. (2003) introduced a control model called DYSCOS for continuous casting at IPSCO Inc. Petrus et al. (2011) proposed a real-time model-based system called CONONLINE for the online control of spray cooling. In order to achieve the goal of real-time control performance, the heat-transfer and solidification model and boundary conditions were usually simplified to obtain accurate results in a very short time. In spite of that the real-time calculations needed in such approaches still required significant computational resources. Another open-loop control approach is the residence time method, and this involves "deceiving" the control system when an abrupt change in casting rate is imminent by giving it a fictitious withdrawal rate that is lower than the actual casting rate (Gilles, 2003). The residence time method adapts well to variations in the casting speed, and can keep the surface temperature smoother under conditions of fluctuating speed, especially with regard to the frequent speed fluctuations seen with continuous casting machines.

In this paper an open-loop dynamic spray cooling control strategy is explained in details, which is an improved residence time control method based on the tracking of velocity and superheat for the continuous casting of steel.

2. Steady-state control model of secondary cooling water

The steady-state model is the basis of the residence time control method, and the precision of this steady-state model is a key factor with regard to its use online. In the steady-state continuous casting operation, the main control method for the use of secondary cooling water is the speed-tie control model, which automatically varies the cooling water according to the casting speed, and the details of this are reported by Inazaki et al. (1984) and Chaudhuri et al. (2010). In the present study, an improved velocity cascade control (VCC) model is employed, as developed by Zhang et al. (2011). The steady-state control model can be expressed as follows:

$$Q_i(V_c) = \begin{cases} \max\left\{Q_{i,\mathrm{lim}},\ \left[Q_{b,i} + Q_{s,i} + Q_{w,i}\right]\right\} & V_c \geq V_{i,\mathrm{lim}} \\ 0 & V_c < V_{i,\mathrm{lim}} \end{cases} \tag{1}$$

$$\text{and } Q_{b,i} = a_i V_c^2 + b_i V_c + c_i \tag{2}$$

$$Q_{s,i} = D_i \times (T_s - T_o) \tag{3}$$

$$Q_{w,i} = F_i(T_w - T_{w,0}) \tag{4}$$

In order to determine the parameters *a, b, c, D* and *F* of the steady-state control model, an offline finite difference model for the heat-transfer and solidification model has been developed, and the governing equations, using the Cartesian coordinate system, are as follows (Wang et al., 2012).

$$C_{p,\mathrm{eff}}\rho\frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda_{\mathrm{eff}}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_{\mathrm{eff}}\frac{\partial T}{\partial y}\right) \tag{5}$$

in which,

$$C_{p,\mathrm{eff}} = \begin{cases} C_p - \Delta H\left(\dfrac{\partial f_{\mathrm{sol}}}{\partial T}\right) & T_{\mathrm{sol}} \leq T \leq T_{\mathrm{liq}} \\ C_p & T > T_{\mathrm{liq}} \text{ or } T < T_{\mathrm{sol}} \end{cases} \tag{6}$$

The fraction of solid forming is given as (Zhang et al., 2015),

$$f_{\mathrm{sol}} = f(T) = \frac{2T^3}{(T_{\mathrm{liq}} - T_{\mathrm{sol}})^3} - \frac{3T^2(T_{\mathrm{liq}} + T_{\mathrm{sol}})}{(T_{\mathrm{liq}} - T_{\mathrm{sol}})^3} + \frac{6TT_{\mathrm{liq}}T_{\mathrm{sol}}}{(T_{\mathrm{liq}} - T_{\mathrm{sol}})^3} + \frac{{T_{\mathrm{liq}}}^3 - 3T_{\mathrm{sol}}{T_{\mathrm{liq}}}^2}{(T_{\mathrm{liq}} - T_{\mathrm{sol}})^3} \tag{7}$$