Research on Dynamic Secondary Cooling Control System Based on Incremental PID Algorithm in Bloom Continuous Casting

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Abstract

An incremental PID control algorithm is presented for the Dynamic Secondary Cooling Zone based on the heat transfer model of the off-line bloom caster. This study is to control the existing cooling systems and the steel casting practices in order to produce steel with best possible quality. One of the most severe defects in continuous casting products is concerned with the cracks provoked by improper design of the spray cooling system. The fitness function of incremental PID algorithm is founded according to metallurgical criteria. This algorithm coupled with a two dimensional heat transfer model based on FVM and metallurgical criteria, can increase water distribution adaptively and improve the process efficiency; As well as, it can calculate the strand temperature distribution and the solid shell profile along the machine; In addition, the relation between the casting speed and liquid core length of the casting slab is found according to the analysis of liquid core length at different casting speeds.

Keywords: BLOOM CONTINUOUS CASTING, DYNAMIC SECONDARY COOLING, FVM, HEAT TRANSFER MODEL, INCREMENTAL PID

1. Introduction

Continuous casting is a method of pouring liquid steel directly from a ladle through a Tundish into mold to form billets, blooms or slabs [1]. The process is schematically shown in Fig. 1.

At the commencement of the casting operation, the mould is closed at the bottom by a dummy bar. As the mould is filled, the liquid steel starts solidifying inside the mould with a solid outer shell and inner liquid core which is called a `strand'. Once the outer shell has sufficient thickness, the dummy bar is withdrawn. The solidified strand is then extracted from the bottom of the mould while the casting continues. Liquid steel continues to pour into the mould to replenish the withdrawn steel at an equal rate. The withdrawal rate depends on the cross section, grade and quality of the steel being produced. Upon exiting the mould, the strand enters a secondary cooling chamber in which the solidifying strand is sprayed with water to promote further solidification [2]. This area preserves cast shape integrity and product quality [3].

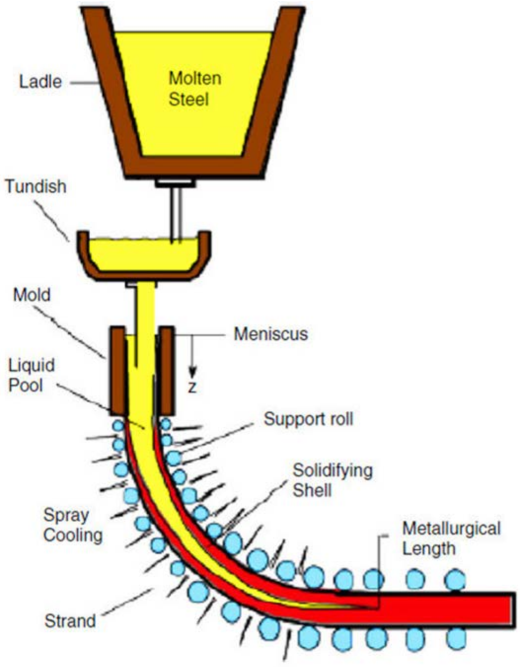


Figure 1. Schematic of a typical continuous casting operation

Since the cooling conditions at the mold and air cooling zone are relatively stable for a given caster, with only the secondary cooling zone (SCZ) capable of being adjusted within a wide range, the quality and output of casting is closely related to the SCZ [4]. Given that the cooling process removes the superheat and the latent heat of fusion at the solidification front, the main cause of internal crack, surface crack and center segregation is the unreasonable secondary cooling structure [5]. These defects should be avoided for the sake of competitiveness in manufacturing. Thus, it is critical to control and optimize the secondary cooling in the whole casting process. It is not feasible to do a lot of experimental trials to calculate the influence of different operational parameters due to economic reasons [6]. Currently, the online dynamic secondary cooling control system is a useful tools for controlling the secondary cooling while the offline model is used to optimize the strand temperature and water distribution in the SCZ [7]. Generally, the offline model is the basis of the online model, and the precision of the offline model is a precondition of applying the online model. Certainly, the heat transfer model is the foundation of the development of the SCZ [8].

In this work, an incremental PID control algorithm is presented for the Dynamic Secondary Cooling Zone based on the heat transfer model of the offline bloom caster. Considering the simulation condition, such as spray cooling pattern, casting speed and casting temperature, a heat transfer model of bloom caster is applied using FVM for the temperature profile. Then an incremental PID algorithm is used to code the secondary cooling water distribution. The procedure corresponds to the fitness function determined by highly conflicting technological and metallurgical requirements. These methods can increase the distribution adaptability and improve the efficiency.

In the present study, a dynamic secondary cooling control system with an incremental PID algorithm in Bloom Continuous Casting is developed. It can calculate the strand temperature distribution and the solid shell profile along the machine. In addition, the relation between the casting speed and liquid core length of the casting slab is found according to the analysis of liquid core length at different casting speeds. This model can improve the equiaxed rate of the bloom and reduce the maximum surface cooling rate and the rate of temperature rise. The optimized bloom has better quality.

2. Mathematcal model

2.1. Heat transfer

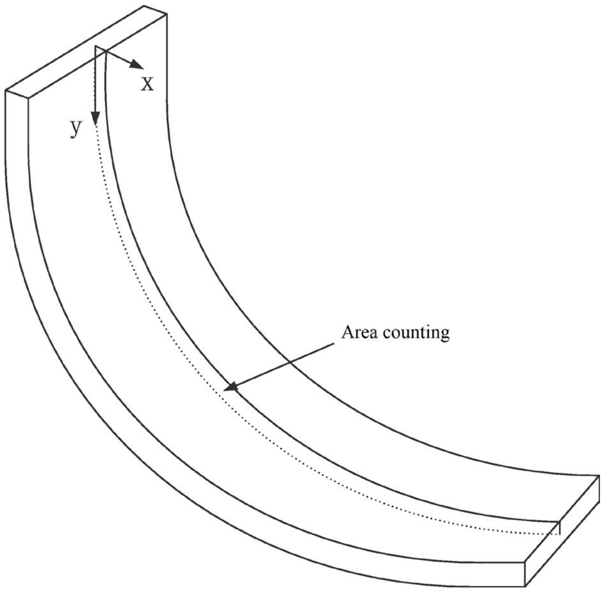


Figure 2. Computational domain of the strand showing the 2D longitudinal section

The energy equilibrium equation of model for the heat transfer in continuous casting is as follows

$$\rho c_p\left(\frac{\partial T}{\partial t}+\upsilon_{cast}\frac{\partial T}{\partial y}\right)=\frac{\partial}{\partial x}\left(\lambda_{eff}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\lambda_{eff}\frac{\partial T}{\partial y}\right)+\rho L\frac{\partial f}{\partial t} \quad (1)$$

In which

$$\rho c_p = f_s\rho_s c_{ps} + (1-f_s)\rho_l c_{pl} \quad (2)$$

$$\lambda_{eff} = \left[f_s\lambda_s + (1-f_s)\lambda_l\right]\left[1+\beta(1-f_s)^2\right] \quad (3)$$

Where υ_{cast} is the casting speed, m/s; ρ is the density, kg/m^3; C_p is the specific heat, J/(kg·K); T is temperature, K; λ is the thermal conductivity, W/(m·K); f the solidification fraction; β the thermal conductivity enhancement factor; L is the latent heat, J/kg; x is the coordinate in the width direction of the strand , m; y is the coordinate in the casting direction of the strand , m;

The subscripts s, l, ref and eff denote solid, liquid, reference and effective, respectively. The thermo-physical properties of steel such as ρ and k are functions of temperature. (1) was used for the online model with an assumption that heat transfer in the slab width was neglected.

2.2. Boundary conditions

In the mould, an average heat flux as a function of casting time is utilized and the boundary heat flux is described by [9]

$$q = 2675200 - B\sqrt{\frac{y}{v_{cast}}}$$

Where q is the mould heat flux, W/m^2 ;B the coefficient relative to heat flux in the mould.

The cooling zone between two rolls was divided into 4 heat transfer regions and the heat transfer coefficients in the offline model were specified for each region by spray cooling, radiation, natural convection and roll contact cooling, respectively[10]. The spray cooling heat transfer coefficient is calculated by [11]

$$h_{spray}=\frac{1570.0w^{0.55}\left[1.0-0.0075(T_{spray}-273.15)\right]}{\alpha}$$

where w is the flux of spray cooling water, L/(m^2·s); T_{spray} is the temperature of spray cooling water, K, and α a machine dependent calibration factor. Nozaki et al. [10], and Laitinenetal. [11] reported the values of α were 4, 4.4 and 5 in their investigations, respectively. In the present study, if only one α constant was used over the entire machine length, the average α would be 4.2.

For the downward facing surface of the slab, h spray was modified to include the effect of slab orientation by multiplying Eq. (6) with (1−0.15cosθ), where θ is the slab surface angle from horizontal. The heat transfer coefficient of the roll contact was taken from the Ref. [11].

Thermal radiation was computed over the entire casting surface except at the roll contact region in the secondary cooling zone.

A standard correlation for natural convection was used, where no spray was mapped to the strand surface. To satisfy the transient calculation of dynamic secondary control, the boundary of the online model was simplified as the upward facing surface of the slab. The overall heat transfer coefficient is determined from an area-weighted average of all heat transfer modes for each segment of the machine as below [12]:

$$h=\frac{h_{roll}A_{roll}+h_{nat}A_{nat}+h_{rad}A_{rad}+h_{spray}A_{spray}}{A_{total}}$$

Where h_{roll}, h_{nat}, h_{rad} and h_{spray} are the heat transfer coefficients of roll contact, natural convection, radiation and spray cooling respectively, W/m^2, and they are calculated similarly as those in the offline model. A_{roll}, A_{nat}, A_{rad} and A_{spray} are the corresponding areas for above 4 heat transfer modes respectively, m^2.

2.3. Incremental PID Algorithm of SCZ

PID (Proportional, interregnal and differential) controller is used widely in kinds of industry circumstance of its simple structure, easy implementation and strong robustness [12]. However, the conventional PID control is limited when applied to a complex physical system, whereas the intelligent PID control fused by both advanced intelligent control thought and conventional PID control has a favorable characteristic [13]. In the secondary cooling zone, the incremental PID algorithm that incorporates with optimization strategies of determining the best operational parameters to the continuous caster is developed.

The regulating principle of PID algorithm in the secondary cooling control is: according to the difference between the billet surface temperature calculated by the mathematical model and the aim temperature, PID controller dynamically controls the secondary cooling water flowrates by feedback and early correction of secondary cooling heat transfer coefficient , making the surface temperature at the aim point of all secondary cooling zones close to the aim temperature, within a certain error range of accuracy.Fig.3 shows the incremental PID algorithm in the secondary cooling control.

The incremental PID algorithm [12] was applied to directly calculate the water flow rate in the offline model, and integral part was considered only when the input perturbation is small during the calculation, i.e.,

$$\begin{cases}|T(n)|>T_c:\Delta L(n)=K_p\left[T(n)-T(n-1)\right]+K_d\left[T(n)-2T(n-1)+T(n-2)\right]\\|T(n)|\le T_c:\Delta L(n)=K_p\left[T(n)-T(n-1)\right]+K_d\left[T(n)-2T(n-1)+T(n-2)\right]+K_iT(n)\end{cases}$$

where ΔL(n) is the water flow rate adjustment, L/min; T_c the tolerance for temperature control which can be set as 5 K;T(n) the difference between the set and calculated surface temperatures, K; and K_p , K_i and K_d are the proportional , integral and differential coefficients, respectively. When the operational con-

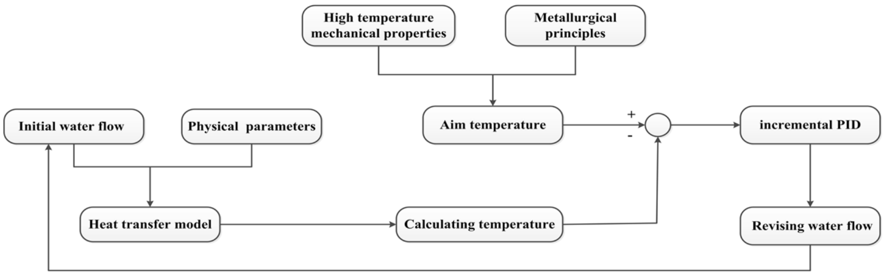


Figure 3. Schematic diagram showing the incremental PID algorithm in the secondary cooling control

dition changes in the continuous casting process, the adjusted water flow rate is:

$$L(n) = L(n-1) + \Delta L(n)$$

Where L(n−1) and L(n) are the water flow rates before and after the adjustment, respectively, L/min.

3. Application and discussion

The PID coupled with the heat transfer model has been applied in a bloom caster. The related technical parameters and thermo-physical properties are listed in Table1. The heat transfer model calculates temperature distribution and shell thickness using offline procedure parameters. Fig. 2 describes the whole process with heat transfer model coupled with PID. Because the temperature in the SCZ cannot be measured, the method to validate the model is shooting nail, measuring the temperature in the air cooling zone.

Table1. Main technical parameters and thermo-physical properties

Parameter	Value
Length×Width×thickness / mm	26000×360×300
Effective mould length / mm	700
Number of secondary cooling zone	4
Steel grade	12Mn2VB
Superheat / °C	25
Liquidus / °C	1521
Solidus / °C	1491
Latent heat / (J·kg−1)	270000
Spray water temperature / °C	25
Ambient temperature / °C	30

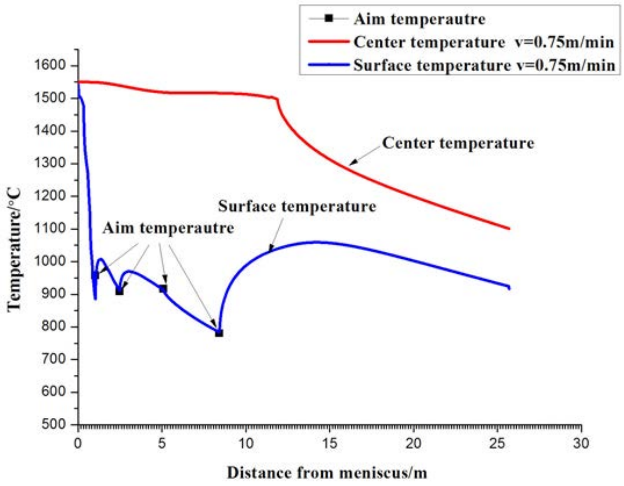


Figure 4. shows the change of the casting slab temperature when casting speeds is 0.75m/min

Fig. 4 shows the surface and center temperatures when casting speed is 0.75m/min. The center temperatures curve show

In the mould, the slab surface temperature starts dropping to form a certain thickness of solid outer shell. Once the outer shell has sufficient thickness, the dummy bar is withdrawn. The solidified strand is then extracted from the bottom of the mould while the casting continues.

In the secondary cooling zone, Dynamic Secondary Cooling Control System based on the incremental PID algorithm dynamically controls the secondary cooling water flowrates, making the surface temperature at the aim point close to the aim temperature, within a certain error range of accuracy. What's more, the slab surface temperature in each of the secondary cooling zone will appear local rebound phenomenon.

In the air cooling zone, the slab surface temperature starts to appear local rebound pheno- menon .and then decreased slowly.

However, in the mould, the center temperature starts to have almost no change.

In the secondary cooling zone, the center temperature has only a very slow change;

In the air cooling zone, due to the thermal conductivity, the center temperature starts to drop. But the slab surface temperature starts to appear local rebound phenomenon surface temperature and center temperature continue to drop slowly after stabilizing .The temperature distribution is more reasonable, which reduces stress cracks. It is consistent with the metallurgical criteria.

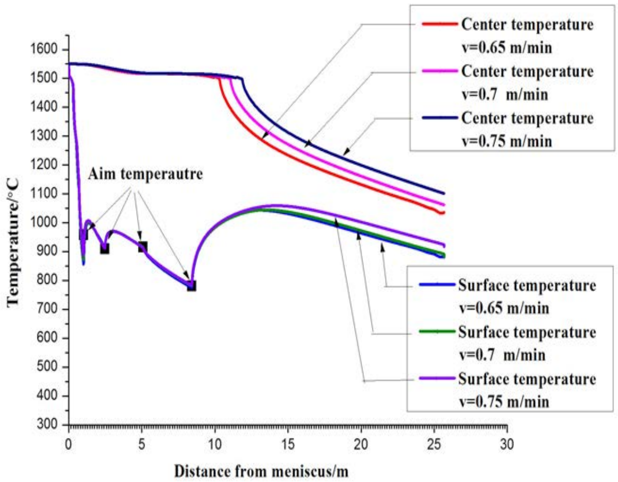
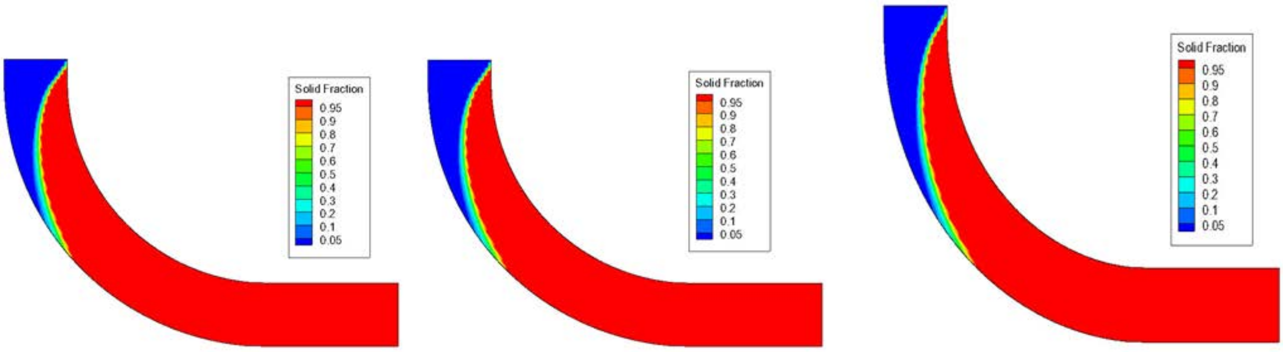


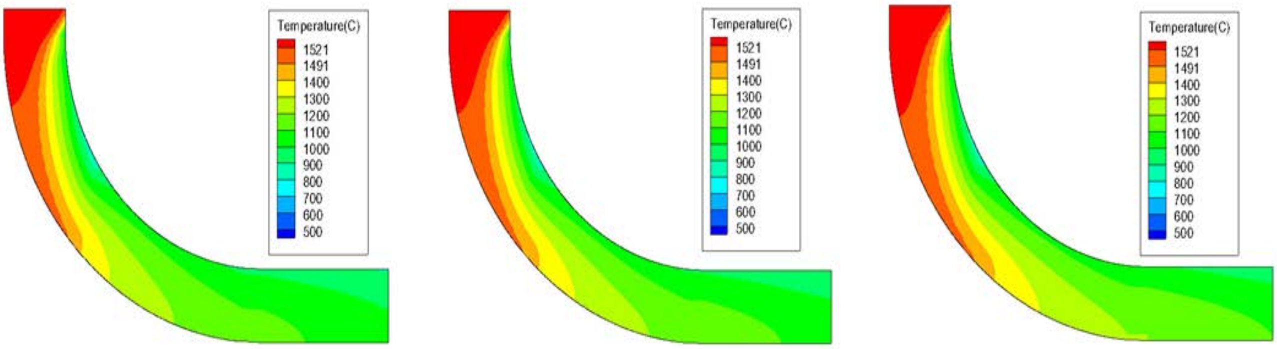
Figure 5. shows the change of the casting slab temperature at different casting speeds

Fig. 5 shows the change of the casting slab temperature at different casting speeds can be seen from the diagram, the casting speed is much higher, the surface temperature is slightly higher, but the center temperature is slightly lower.



(a)V=0.65m/min (b)V=0.7m/min (c)V=0.75m/min

Figure 6. shows the temperature distribution of the casting slab at different casting speeds



(a)V=0.65m/min (b)V=0.7m/min (c)V=0.75m/min

Figure 7. shows the Solid and liquid distribution of the casting slab at different casting speeds

Fig.6 shows the temperature distribution of the casting slab at different casting speeds .

Fig.7 shows the Solid and liquid distribution of the casting slab at different casting speeds.

Furthermore, Fig.6 and Fig.7 show The change of liquid core length of the casting slab at different casting speeds which can be seen from the diagram, the casting speed is more higher, the liquid core length will increase, In order to better describe the relationship of the liquid core length and casting speed, the data of liquid core length at different casting speed is gotten by simulation of Dynamic Secondary Cooling Control System, as shown in Table2. Data using polynomial fitting method is fitted to the curve in Fig.8, and the relevant expression is:

$$y = 10x^2+1.5x+5.11$$

Table2. The change of liquid core length of the casting slab at different casting speeds

Casting speed(m/min)	liquid core length (m)
0.65	10.31
0.7	11.06
0.75	11.86

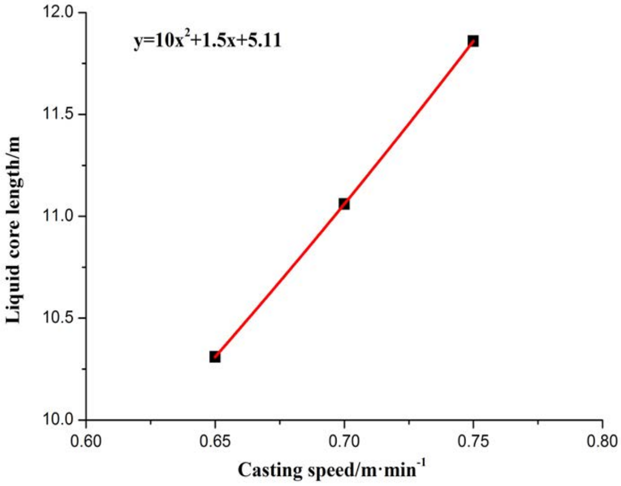


Figure 8. shows the change of liquid core length of the casting slab at different casting speeds

4. Conclusions

In this paper, offline procedure based on The PID coupled with the heat transfer model is developed in Bloom Continuous Casting, in which the error is controlled less than 5%. The temperature distribution and the Solid and liquid distribution is calculated using offline procedure.

The change of the casting slab temperature when casting speeds is 0.75m/min and the change of the casting slab temperature at different casting speeds is obtained.

The temperature distribution and the Solid and liquid distribution at different casting speeds is calculated.

In addition, the relation between the casting speed and liquid core length of the casting slab is found according to the analysis of liquid core length at different casting speeds. The casting speed is much higher, the liquid core length will increase .the relevant expression using polynomial fitting method is: $y = 10x^2+1.5x+5.11$.

It is evident that the application of PID and a numerical heat transfer model to simulate optimal operating conditions for a steel continuous caster is a powerful tool for optimizing the secondary cooling process.

A simulation generated by the PID shows the modifications, which corresponds with the model ingot quality.

The PID with adaptive method in the crossover and mutation process can improve the optimized efficiency of the algorithm.

Conflict of interest

The author confirms that this article content has no conflict of interest.

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