The Optimization of Secondary Cooling Water Distribution

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Abstract—In the continuous casting secondary cooling stage, since the steel component and on-site parameters are different, the traditional water distribution model sometimes induces large fluctuation of casting billet's exterior temperature, this status will affect quality of casting billet. So, according to certain metallurgical criterion and target temperature of casting billet, we have established a new secondary cooling water distribution model to optimize the secondary cooling water distribution scheme, and achieve the purpose of improving the quality of casting billet.

Keywords—continuous casting; secondary cooling; secondary cooling water distribution model; casting quality.

I. INTRODUCTION

Continuous casting is one of the key technology in steel making technology, but secondary cooling is one of the important link in continuous casting. The secondary cooling has closely something with the output and quality of continuous casting, when other parameters are constant, the strength of secondary cooling increases, the casting speed increases, and the output of casting machine increases. Also, some research has been shown that, a lot of quality defects of casting billet are related to the secondary cooling[1], such as the crack of casting billet, surface crack, bulging, central segregation and porosity[2]. So, set up a new secondary cooling water distribution model and optimize the secondary cooling water distribution system are very important to continuous casting.

The existing model of secondary cooling water distribution when controlling water distribution, it mainly considering the effects of casting speed changes in water, rarely consider the influence of liquid steel super heat[3,4]. In this paper, at the same time considering the effect of casting speed and degree of super heat, established a new model of secondary cooling water distribution to control the water distribution.

In this paper, take the 60Si²MnA casting billet as the research object, established the mathematical model of continuous casting, simulation of casting solidification heat transfer process. According to certain metallurgical criterion, according to the slab target temperature determine criterion, set up secondary cooling water distribution control model, optimize the continuous casting secondary cooling system, improve the quality of casting billet and increase the production of the caster.

II. MATHEMATICAL MODEL OF SOLIDIFICATION HEAT TRANSFER

A. Set up the mathematical model

When set up the mathematical model, some factors have little effect on the calculation results, in order to simplify the model and reduce the complexity of the model, these factors can be properly ignored or simplified[5,6]. The assumption of setting up the mathematical model of solidification heat transfer is as follows:

- Only considering the heat transfer of casting billet thickness direction, while ignoring the heat transfer of width direction and casting direction.
- When the site production conditions are relatively stable, the temperature of casting billet in a certain position along the casting billet does not change over time(The temperature in the casting billet is in unsteady state);
- Assume that during the whole solidification process, the size of the casting billet without any change;
- The casting billet is central symmetry;
- The thermophysical parameters of the casting billet are equivalent to constant;
- The casting billet is considered to be uniform cooling in the same secondary cooling zone;
- Steel is isotropic;
- In secondary cooling zone, the contact heat transfer between roller and casting billet can be ignored, and the self radiation heat transfer of casting billet can also be ignored[7].

The solidification heat transfer process can be shown in fig.1.

Fig. 1. Casting billet solidification diagram

Suppose that take a model from the mold meniscus along the center of the casting billet, the model with the thickness is dx , width is dy , height is dz , the model and casting billet move down along the casting direction.

Assume that the thickness direction of the casting billet is x , the temperature distribution of the solidified shell is $T(x,y,t)$, so the mathematical model of solidification heat transfer is given as bellow:

$$\rho C (\partial T / \partial t) = \partial / \partial x (\lambda \partial T / \partial x) + \partial / \partial y (\lambda \partial T / \partial y) \quad (1)$$

In the equation(1), T is the temperature of the casting billet; t is the time; C is the specific heat capacity of the liquid steel; ρ is density of the liquid steel; λ is the thermal conductivity; x and y is the coordinate of the cross-section of the casting billet.

B. Initial Conditions And Boundary Conditions

1) *Initial Conditions*: in the beginning, $t=0$, $x=0$, $y=0$, so the casting billet has bellow conditions:

a) The temperature of the liquid steel is equal to the pouring temperature.

b) The solidified shell thickness is zero.

2) *Boundary Conditions*: the casting billet has bellow conditions:

a) *In the center of the casting billet*: the heat transfer of the casting billet is symmetrical, so it can get bellow equations:

$$(\lambda \partial T / \partial x)_{x=0} = (\lambda \partial T / \partial y)_{y=0} = 0 \quad (2)$$

b) *In the surface of the casting billet*:

$$(\lambda \partial T / \partial x)_{x=\pm a/2} = (\lambda \partial T / \partial y)_{y=\pm a/2} = q_s \quad (3)$$

In the equation(2), q_s is the surface heat flux, in different secondary cooling zone, the boundary conditions are different, the equations are given as bellow:

- Mold:

$$q_s = A - B\sqrt{t} \quad (4)$$

- Secondary cooling zone:

$$q_s = h(T_b - T_w) \quad (5)$$

- Air cooling zone:

$$\varepsilon \sigma [(T_b + 273)^4 - (T_o + 273)^4] \quad (6)$$

In these equations, t is the time; h is the heat transfer coefficient between casting billet and water; T_w is the surface temperature of casting billet; T_o is the environment temperature; σ is J Bozeman constant; ε is objects blackness; A and B are experimental constants.

C. Model Solution

he casting billet belong is centrosymmetric and the heat transfer is two-dimension heat transfer. So, it can be considered that the temperature of the cross-section of casting billet is also centrosymmetric. So, it just needs to take a quarter of the cross-section as the research model, then simulate the model through finite-difference method. The node mesh diagram of the cross-section is shown in fig.2.

The difference equation of the cross-section in different position can be obtained by doing differential transformation to mathematical model of solidification heat transfer.

Fig. 2. Node mesh diagram of casing billet

After calculation, nine difference equations of different node can be obtained, the equations of corner node and internal node are given as below :

1) *Corner Node A(0,0)*:

$$T_{0,0}^{n+1} = T_{0,0}^n + \lambda (\Delta t / \rho c) [(T_{1,0}^n - 2T_{0,0}^n + T_{-1,0}^n) / (\Delta x)^2 + (T_{0,1}^n - 2T_{0,0}^n + T_{0,-1}^n) / (\Delta y)^2] \quad (7)$$

2) *Internal Node*:

$$T_{i,j}^{n+1} = T_{i,j}^n + \lambda (\Delta t / \rho c) [(T_{i+1,j}^n - 2T_{i,j}^n + T_{i-1,j}^n) / (\Delta x)^2 + (T_{i,j+1}^n - 2T_{i,j}^n + T_{i,j-1}^n) / (\Delta y)^2] \quad (8)$$

All the equations can be solved independently, but when the differential equations are replaced by difference equations, a certain amount error was produced. In order to reduce the error, it's required to set the Δx , Δy and Δt were very small, at the same time, Δx , Δy and Δt must satisfy the stability of the differential equation.

For the two-dimension heat transfer equation, the stability of the differential equation is:

$$0 < \lambda (\Delta t / \rho c) [1 / (\Delta x)^2 + 1 / (\Delta y)^2] \leq 1/2 \quad (9)$$

D. Determination Of Thermal Physical Parameters

1) *Steel Solidus And Liquids Temperature*: The solidus and liquids temperature can be calculated by empirical formula.

a) *Liquids Temperature*:

$$T_l = 1536 - \left\{ \begin{aligned} &90[C\%] + 6.2[S\%] + 1.7[Mn\%] + 28[P\%] + 40[S\%] + 2.6[Cu\%] + \\ &3.1[Ni\%] + 1.3[Cr\%] + 3.6[Al\%] + 2.0[Mo\%] + 2.0[V\%] + 18[Ti\%] \end{aligned} \right\} \quad (10)$$

b) *Solidus Temperature*:

$$T_f = 1536 - \left\{ \begin{aligned} &415.5[C\%] + 12.3[S\%] + 6.8[Mn\%] + 124.5[P\%] + \\ &183.9[S\%] + 4.3[Ni\%] + 1.4[Cr\%] + 4.1[Al\%] \end{aligned} \right\} \quad (11)$$

2) *Specific Heat Capacity Of Steel*

Usually, as the temperature increases, the specific heat capacity will increases. But in the environment of high temperature, the specific heat capacity does not change a lot, so, it can be regarded as constant in counting. Normally the liquid specific heat capacity of the steel is 756J/(kg·°C), and the solid specific heat capacity of the steel is 662J/(kg·°C).

But when calculating the specific heat of two-phase region, it should include latent heat of solidification, and it can be calculate by using equivalent specific heat method.

$$C_{eff} = (C_s + C_l)/2 + L_f/(T_l - T_s) \quad (12)$$

As shown in the equation(12), C_{eff} is the specific heat capacity in two-phase region; C_s is the solid specific heat capacity; C_l is the liquid specific heat capacity; L_f is the latent heat of solidification; T_l is liquids temperature; T_s is solidus temperature.

In this paper, the thermal physical parameters are shown in table 1.

TABLE I. THE THERMAL PHYSICAL PARAMETERS OF THE STEEL

Steel grade	Grade	C_s /J/(kg · °C)	C_l /J/(kg · °C)	L_f /J/(kg · °C)
Spring steel	60Si2MnA	662	756	260.4

3) *Thermal Conductivity*

In this paper, the thermal conductivity of the solid phase region is usually treated as constant, it can be calculated by below equation(T_s is the solidus temperature).

$$\lambda = 15.884 + 0.011495 \times T_s \quad (13)$$

And the thermal conductivity of the liquids phase region is 1~4 times of the solid phase region, that is $\lambda_l = m\lambda$, m is 4 when the casting billet is in mold; m is 2 when the casting billet is out of the mold and is not yet reach to the secondary cooling; m is 1 when the casting billet reached to the secondary cooling.

4) *Steel Liquid Density*

In this paper, when building the model, in order to calculate conveniently, it is assumed that the density of the steel has no change in the process of solidification. So, when calculating, the density of low carbon steel in liquid phase region is 7000kg/m³; the high temperature solid phase density is 7400kg/m³; the density of two-phase region is 7200kg/m³.

So, with the thermal physical parameters all above, the difference equations of the mathematical model of solidification heat transfer. Then, it can get the water distribution and water distribution parameters of each secondary cooling zone.

III. OPTIMIZATION OF THE SECONDARY COOLING WATER DISTRIBUTION SYSTEM

In the process of continuous casting of the steel, many parameters would affect the effect of the secondary cooling, such as steel composition, casting speed and super heat[8]. So in this paper, it considering the affect of all above parameters in secondary cooling process and established the secondary cooling water distribution model which has shown below:

$$Q = A_i v^2 + B_i v + C_i + D_i \Delta T \quad (14)$$

As shown in equation(14), Q_i is the water content of each secondary cooling zone; v is the casting speed; A_i , B_i , C_i , D_i are the coefficients which got according from the empirical values and the simulation optimization; ΔT is the super heat of the steel.

Firstly, according to the metallurgical criterion, it set up the target temperature of different secondary cooling zone; Secondly, this paper according to the mathematical model of solidification heat transfer to describe the solidification process of casting billet with the simulation software, it also obtained water distribution parameters and water content of different secondary cooling zone, the results can be used to direct production; At the same time, the regression function can control the production so as to save time and improve control timeliness.

IV. OPTIMIZATION RESULTS VERIFICATION

If you want to validate the rationality of the secondary cooling water distribution model and system, it is necessary to validate from the following aspects, such as the water quantity optimization result and the surface temperature verification results.

In this paper, the research object is spring steel and the grade of the steel is 60Si2MnA and the casting machine is No.1 caster of a steel plant. The parameters of the caster are shown in table 2.

TABLE II. THE TECHNOLOGICAL PARAMETERS OF THE CASTER

Item	Parameter	Item	Parameter
Caster radius	12m	Mould length	7.04m
Caster fillet radius	R12mm	Mould effective length	6.30m
Cross-section size	300*360mm ²	Secondary cooling zone 1	0.45m
Steel grade	60Si2AMn	Secondary cooling zone 2	1.2m
Casting billet weight	4.25~5.05T	Secondary cooling zone 3	3.8m

A. Water Distribution Optimization Results Verification

After optimizing, the water quantity of different secondary cooling zone in different casting speed is shown in table 3.

TABLE III. WATER QUANTITY OF DIFFERENT SECONDARY COOLING ZONE

Water quantity of different zone (L/min)	Casting speed (m/min)					
	1.0	1.2	1.4	1.6	1.8	2.0
Zone 1	16.45	22.83	30.00	36.00	50.83	73.33
Zone 2	13.83	24.67	38.50	43.50	54.67	80.83
Zone 3	6.17	10.33	18.00	24.00	32.00	52.00

After optimization, the total water quantity of the secondary cooling is reduced a lot, we can see the change in table 4.

TABLE IV. TOTAL WATER QUANTITY OPTIMIZATION RESULT

Secondary cooling zone	Water quantity L/min	
	Before optimization	After optimization
Zone 1	50	40
Zone 2	70	47
Zone 3	35	25
Total water quantity	129	112

B. Surface Temperature Of casting billet verification

When verifying the surface temperature of the casting billet, it used infrared temperature measuring instrument to measure the surface temperature of casting billet, then comparing the calculated results with the measured results, and the comparison results are shown in table 5.

TABLE V. COMPARISON RESULTS

Casting speed (L/min)	Surface Temperature of 1 zone end(°C)		Surface Temperature of 2 zone end (°C)		Surface Temperature of straightening point(°C)	
	Measure result	Calculate result	Measure result	Calculate result	Measure result	Calculate result
1.0	980	976	945	941	920	917
1.2	990	986	960	956	940	937

From comparison results of table 5, it can be obtained that the error between calculated results and measured results is very small and meet the error range, so, the mathematical model of solidification heat transfer is reasonable.

V. CONCLUSION

The optimization of secondary cooling scheme has a very important effect on the improvement of the quality of casting billet but also increase the output yield of the casting machine.

The mathematical model of solidification heat transfer can be used to simulate the solidification process of the casting billet but also provides the basis for optimizing the secondary cooling water distribution system.

The verification results show that the secondary cooling water distribution model meets the technology requirements and the calculation results are agreement with the actual results. And the water distribution system can improve the quality of the casting billet, optimize the secondary cooling system and direct production.

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