Y. R. LI, C. N. ZHANG

ISSN 0543-5846
METABK 58(1-2) 59-62 (2019)
UDC – UDK 669.18.163.002.3:621.56/.59:66.093:519.7:529.7/536.45=111

ANALYSIS OF THE SECONDARY COOLING WATER DISTRIBUTION SYSTEM BASED ON DIFFERENTIAL EVOLUTION ALGORITHM

Received – Primljeno: 2018-06-26
Accepted – Prihvaćeno: 2018-10-15
Original Scientific Paper – Izvorni znanstveni rad

In the continuous casting, the secondary cooling water distribution system has a decisive effect on the quality of billets. An intelligent optimization strategy, which is different from the traditional mode, is adopted to establish a new water distribution mode. In order to match the water volume of each segment, the objective function is designed by the metallurgical criterion and constraint conditions, and the optimal solution is obtained by differential evolution algorithm. It has been verified that the overshoot is low, the total water volume is reduced, and the quality of billets is significantly improved.

Key words: continuous casting; billet; secondary cooling water distribution; differential evolution algorithm; time/temperature

INTRODUCTION

The quality and yield of billets are closely related to the secondary cooling. Studies have shown that the quality of billets, such as internal cracks, surface cracks, drums, rhombus square and central segregation, is mainly attributed to the unreasonable secondary cooling systems when other process conditions are unchanged[1,2].

In the process of cold water distribution, the working conditions are complex, and the heat transfer model of continuous casting belongs to the nonlinear partial differential boundary value problem[3]. The traditional optimization function is difficult to solve[4]. After the optimization of the secondary cooling water distribution system, the total water volume decreased, the surface temperature distribution tended to be flat, and the quality of billets increased significantly[5].

MATHEMATICAL MODEL OF SOLIDIFICATION HEAT TRANSFER

Equation of solidification heat transfer

Taking the billets as the research object, considering the solidification and heat transfer behavior of billets in the secondary cooling zone, combined with the requirements of the control, a mathematical model for the solidification and heat transfer of the two-dimensional billets was established [6]. For the billets, its radial heat transfer is much larger than the axial heat transfer, so the radial heat transfer is only considered to ignore the axial heat transfer in the calculation, which can simplify the heat transfer problem from three-dimensional to two-dimensional, and the unsteady heat transfer control equation is as follows:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(k\frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k\frac{\partial T}{\partial y}) \qquad (1)$$

In the formula, ρ is the density of the billet (Kg/m^2), c_p is a specific heat(J/(kg·°C)), k is the coefficient of thermal conductivity (W/(m·°C)), S is an internal heat source (J/(m^3·s)), T is the surface temperature (°C).

Multi-objective optimization

For the control of the volume of secondary cooling water in the cooling process of billets, due to the complexity of the temperature field changes, the optimal solution can't be obtained by the traditional single-objective function optimization method with constrained. This paper quantifies the corresponding parameters and obtains the objective function which meets the requirements [7].

(1) Determination of surface temperature

According to the steel type, size and casting speed, etc., the ideal surface temperature T' of billets is determined, and the actual water distribution is adjusted so that the surface temperature T of the control point is infinitely close to T'. The objective function is as follows:

$$F_1(R) = \sum_{i=1}^{n} l_i \mid T_i - T_i' \mid^2 \qquad (2)$$

In the formula, l_i is the each segment length of the secondary cooling, n is the total number of the secondary cooling, the corresponding control vector for each segment is $\{R|r_1, r_2, \cdots r_n\}$.

Y. R. Li. e-mail: lyr7879@163.com,Institute of Applied Technology, University of Science and Technology Liaoning, China; C. N. Zhang,School of Software, University of Science and Technology Liaoning,China

(2) Surface temperature recovery rate and cooling rate

The thermal stress produced by the rapid change of surface temperature before solidification of billets is easy to cause crack. Therefore, when the billet is traveling in each cooling segment, the temperature should be prevented from rising or falling too quickly. The temperature is controlled along the direction of pulling.

$$F_2(R)=\int_0^L \max\left(\frac{\partial T}{\partial z}-P^B,0\right)^2 dz+\int_0^L \max\left(P^C-\frac{\partial T}{\partial z},0\right)^2 dz \qquad (3)$$

In the formula, P^B is the maximum surface temperature recovery rate (°C/m), P^C is the maximum cooling rate (°C/m), L is the total length of the secondary cooling(m).

(3) Straightening point temperature

In order to avoid transverse cracks in the brittle temperature region of steel, the surface temperature at the straightening point should be higher than its brittle temperature T^B in the secondary cooling system.

$$F_3(R)=\max(T_B-T,0)^2 \qquad (4)$$

The above three objective functions are integrated, and different factors β_i are selected according to the weight, corresponding to the function, which satisfies $\beta_1 + \beta_2 + \beta_3 = 1$. The optimized objective function is:

$$F'(R)=\sum_{i=1}^{3}\beta_i F_i(R) \qquad (5)$$

OPTIMAL MODEL OF SECONDARY COOLING WATER DISTRIBUTION BASED ON DIFFERENTIAL EVOLUTION

Optimization of differential evolution algorithm

The Differential Evolution Algorithm (DE) is similar to the legacy algorithm. that is, using mutation operations to generate new individuals, then cross and select the operation, and repeatedly execute to obtain the optimal solution.

The DE algorithm includes three important parameters: population size N_p, scaling factor F, and crossover probability CR. According to experience, the size of the population should be moderate, if it is too large, it will take a lot of calculation time; if it is too small, it will reduce the diversity of the population and the convergence cannot be guaranteed, which is usually set to 5-10 times of the dimension, that is $N_p \in [5Q, 10Q]$. The scaling factor is used to control the scaling of the differential vector and take $F \in [0,5, 1]$. The crossover probability is used to adjust the diversity of the population. It is important to note that the crossover probability is too large, the algorithm will easily become a random algorithm, the usual range is $CR \in [0,1]$. The following are the improved parameters:

$$\begin{cases} F(k+1)=F(k)-\dfrac{F(0)-F_{\max}}{k_{\max}} \\ CR(k+1)=CR(k)-\dfrac{CR(0)-CR_{\min}}{k_{\max}} \end{cases} \qquad (6)$$

In the formula, $F(0)$ and $CR(0)$ are the initial generation scaling factor and crossover probability. $F_{\max}$ and $CR_{\min}$ respectively are the maximum value of the scaling factor and the minimum value of the crossover probability in the iteration. $k_{\max}$ is the maximum number of iterations.

Encoding rules and algorithm steps

The size of the population is m, and the number of water distribution segment is n. The traditional differential evolution algorithm uses the mapping method, such as $T \rightarrow R$ mapping, encoding (1,4, -1,3, -1,5,6), that is, the volume of water in the water distribution segment 1 and 2 is mapped to the 0th individual, the 3th is mapped to the 1th ,etc.. The distribution of the mapping method is simple and clear, but the repetitive individual will appear in the DE algorithm because of the mutation operation. If this encoding is adopted, the unnecessary repeated solution will be obtained and the optimal solution will be missed. Based on this, an array representation is designed in this paper, which is to set a two-dimensional array $A[m][n]$, the first subscript identifies the individual number, the second subscript identifies the water distribution segment, and the array value identifies the volume of water in the corresponding each segment.

Water distribution

Considering the quality requirements of billets, the surface temperature in the secondary cooling zone distribution process should be reduced uniformly along the direction of pulling. The distribution of water volume is influenced by the factors such as casting speed, steel type, billet size, etc., in order to ensure the quality of billets, the cooling strength of secondary cooling must satisfy a certain functional relationship:

$$Q_i = A_i V^2 + B_i V + C_i \qquad (7)$$

In the formula, Q_i is the volume of water in each segment (L / min), A_i, B_i, C_i is the adjustment coefficient, V is pulling speed (m / min).

The solidification rate is inversely proportional to the time during the cooling process of billets in the secondary cooling zone, and the water distribution formula for each segment of the secondary cooling is obtained.

$$Q_1 : Q_2 : \cdots Q_n = 1/\sqrt{H_1} : 1/\sqrt{H_2} : \cdots 1/\sqrt{H_n} \qquad (8)$$

$$Q = Q_1 + Q_2 + \cdots + Q_n \qquad (9)$$

In the formula, Q is the total volume of water (L / min), H_i is the distance from the each segment middle point of the secondary cooling to the liquid level of the crystallizer.

Experimental analysis

Taking the billets continuous casting process of a steel plant as the test object, the differential evolution of the secondary cooling water distribution system was

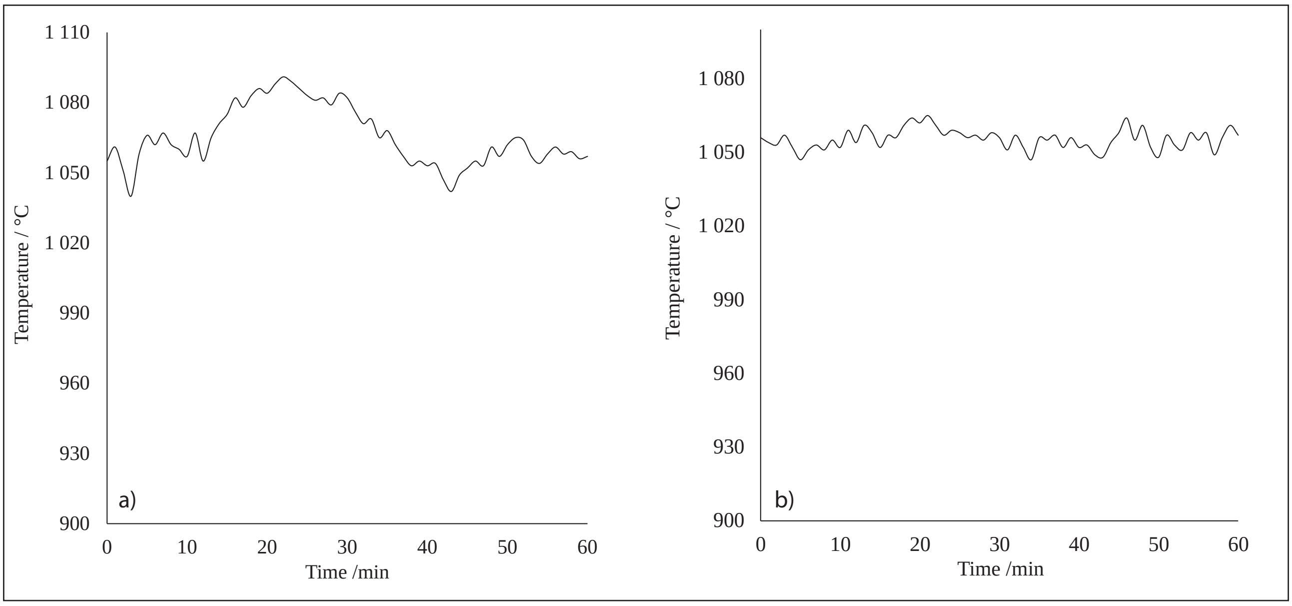

Figure 1 Comparison of surface temperature of billets
(a) Surface temperature of billets before optimization (b) Surface temperature of billets after optimization

optimized. The secondary cooling area is divided into 4 segments, the size of the section is 0,15×0,15 m. The physical parameters are as follows: the specific heat capacity is 660 J/(kg·K) in the solid phase, it is 825 J/(kg·K) in the liquid phase. The density is 7×10^3 kg/m^3 in the liquid phase, it is $7{,}4\times10^3$ kg/m^3 in the solid phase. The thermal conductivity is 29,3 W/(m·K) in the solid phase, it is 116,6 W/(m·K) in the liquid phase. The pouring conditions are as follows: the pouring temperature is 1 550℃, the superheat is 35 ℃, the temperature is 1 530 ℃ in the liquid phase, the temperature is 1 500 ℃ in the solid phase, the temperature of the cooling water is 25 ℃, the pull speed is 1.8 m/min. The iteration number of DE is 400 times, the crossover rate is 0,75, the mutation rate is 0,5. To see the effect of algorithm application, see Tables 1,2; Figures 1,2.

Through comparison of the amount of water in Table 1, it is found that the volume of water after optimization is significantly reduced. The defect of billets is better controlled in Table 2. After intelligent water distribution control, the surface temperature changes smoothly, and the overshoot is low, and the adjustment time interval is shortened.

Table 1 **Comparison of water volume before and after optimization**

Segment of the secondary cooling	Water volume	
	Before optimization	After optimization
1	212,3	131,6
2	182,6	105,4
3	159,1	82,6
4	127,8	62,5

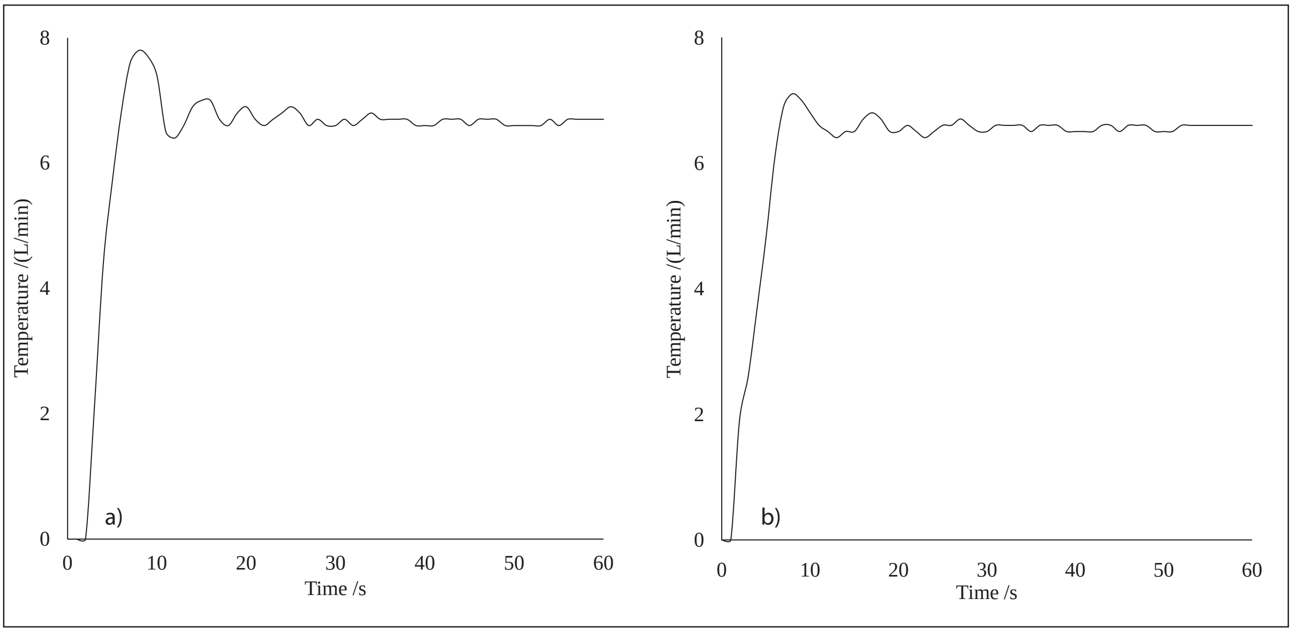

Figure 2 Comparison of step water flow
(a) step water flow before optimization (b) step water flow after optimization

Table 2 **Analysis of the results of low times test**

Defect type	0 level		0,5 level		1 level		1,5 level	
	TM	OM	TM	OM	TM	OM	TM	OM
Corner crack	57,6	67,8	25,7	11,5	0	0	0	0
Middle crack	0	0	45,2	55,6	32,5	21,4	0	0
Central looseness	47,1	54,9	44,2	28,3	2,3	0	0	0
Center shrink hole	29,7	56,4	35,3	31,8	9,5	0	5,2	0

Note: TM-- Traditional method;OM-- Optimized method

CONCLUSIONS

The traditional water meter method has the uneven distribution problem of secondary cooling water. The water distribution system based on intelligent optimization control is applied to optimize the convergence and accuracy of the algorithm. In the secondary cooling control, the amount of water regulation overshoot is low and the total water is reduced, the calculated surface temperature changes are more reasonable, the experimental results of low frequency detection show that the quality of billets is effectively improved.

Acknowledgments

This work was supported by the science and technology support program (2016HZPY09) from Liaoning Education Department.

REFERENCES

[1] Kalitaev A.N.,Tutarova V.D.,Shapovalov A.N..Effect of continuous casting parameters on quality of billets manufactured by UMMC steel LLC[C]. Materials Engineering and Technologies for Production and Processing III 265(2017), 952-961.

[2] Smirnov A.N., Kuberskii S.V., Smirnov, E.N., Verzilov A.P. Maksaev E.N. Influence of meniscus fluctuations in the mold on crust formation in slab casting[J]. Steel in Translation 47(2017)7, 478-482.

[3] Yamasaki Norimasa, Shima Shozo, Tsunenari Keiji, Hayashi Satoru, Doki Masahiro. Particle-based numerical analysis of spray water flow in secondary cooling of continuous casting machines[J]. ISIJ International 55(2015)5, 976-983.

[4] Erdbrink Christiaan D., Krzhizhanovskaya Valeria V. Differential evolution for system identification of self-excited vibrations[J]. Journal of Computational Science 10(2015), 360-369.

[5] Cárdenas-Montes Miguel.Incorporating more scaled differences to differential evolution[C]. Hybrid Artificial Intelligent Systems 10334(2017), 101-112.

[6] Assuncao C., Tavares R., Oliveira G.Improvement in secondary cooling of continuous casting of round billets through analysis of heat flux distribution[J]. Ironmaking and Steelmaking 42(2015)1, 1-8.

[7] Drozdz P..Influence of Cooling Conditions on a Slab's Chill Zone Formation during Continuous Casting of Steel[J]. Archives of Metallurgy and Materials 62(2017)2, 911-918.

Note: The responsible for English is Zhang Yue Ru Liaoning, China