Y. R. LI, C. N. ZHANG

ISSN 0543-5846
METABK 58(3-4) 239-242 (2019)
UDC – UDK 669.18:669.163-532.57:621.56/.59-66.093/536.1:536.5=111

INTELLIGENT OPTIMIZATION STRATEGY ANALYSIS OF SECONDARY COOLING WATER DISTRIBUTION FOR BILLET

Received – Primljeno: 2019-01-02
Accepted – Prihvaćeno: 2019-03-25
Original Scientific Paper – Izvorni znanstveni rad

Aiming at the optimization of secondary cooling water distribution system for billet, an intelligent optimization model is established. The objective function is set according to metallurgical criteria, and the optimal solution is obtained by particle swarm optimization, which is applied to dynamic secondary cooling water distribution system. The experimental results show that at different casting speeds, all the indexes of the billet meet the requirements, the total water volume decreases obviously, the overshoot is low, and the water volume of each section meets the expectation.

Key word: steel; casting speeds; secondary cooling water distribution; temperature; total water volume

INTRODUCTION

Secondary cooling of continuous casting is to make the surface temperature of slab meet the technological requirement by adjusting the spray amount of water in each section of secondary cooling zone, that is, to keep the high plasticity[1]. In this way, defects such as internal cracks, surface cracks, bulging, diamond square and center segregation can be effectively avoided[2,3].

Using the traditional partial differential equation method to solve the particularity of the water volume optimization in the secondary cooling water distribution, its efficiency is not high [4], this paper proposes an improved particle swarm optimization algorithm, which introduces chaotic mechanism to enhance the ergodicity and diversity of the algorithm, and has better performance[5,6]. After the application of the scheme, all the indexes of the slab meet the expectation, the total water volume decreases greatly, and the water volume of each section keeps stable at different casting speeds, which effectively improves the quality of the slab.

OBJECT FUNCTION

Heat transfer equation for solidification

Taking billet as the research object, the width direction, thickness direction and forward direction of billet are set to be *x, y, z* respectively. Because the heat transfer of *z* axis is much smaller than that of other two axes, it is neglected [7]. Moreover, the size change of billet in tension straightening is neglected in heat conduction, and the thermal properties (specific heat capacity, density, etc.) are assumed not to change with temperature. The governing equations of unsteady heat transfer are as follows:

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

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

Determining the objective function

The objective function is designed according to metallurgical criteria, i is defined as the identification of cooling section and R is the control vector of each section, $\{R \mid r_1, r_2, ... r_n\}$, the corresponding parameters are quantified to obtain the objective function that meets the requirements [8].

Surface temperature

The ideal surface temperature T' of slab is determined according to steel grade, size and casting speed. The actual water distribution is adjusted so that the surface temperature T of 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 length of each section of secondary cooling and n is the total number of secondary cooling sections.

Surface temperature recovery rate and cooling rate

The thermal stress caused by the rapid change of surface temperature before solidification of billet is liable to cause cracks. Therefore, the billet should avoid

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

too fast rise or decrease of temperature in each cooling section. Temperature should be controlled along the direction of billet drawing. The maximum surface temperature recovery rate is set to P^B and the maximum cooling rate is P^C.

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

Straightening point temperature

In order to avoid transverse cracks in the brittle temperature zone of steel grades, it is necessary to ensure that the surface temperature at the straightening point is higher than its brittle temperature T_B in the secondary cooling system.

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

Water consumption

In the process of spraying water in the secondary cooling zone, the total amount of water should be reduced as far as possible.

$$F_4(R) = \sum_{i=1}^{n} r_i \quad (5)$$

The above four objective functions are integrated, and different influencing factors β_i are selected according to different weights to correspond to the function, which satisfies $\sum_{i=1}^{3} \beta_i = 1$. The optimized objective function is as follows:

$$F(R) = \sum_{i=1}^{4} \beta_i F_i^{'}(R) \quad (6)$$

OPTIMIZATION MODEL OF SECONDARY COOLING WATER DISTRIBUTION BASED ON PARTICLE SWARM OPTIMIZATION(PSO)

Particle swarm optimization

PSO algorithm is a simulated evolutionary process to obtain the optimal solution through communication and cooperation among individuals. Each particle has two attributes of speed and location, and the solution of the problem corresponds to the current position of the particle. In Q dimensional space, the control vector R of each segment is mapped to particles and initialized to $\{r_1, r_2, \dots r_n\}$. The chaotic mechanism is used to optimize the process of particle optimization. The search steps are as follows:

(1) Define the initial region, setting Q dimensional initial state vector $Q_0 = (Q_{01}, Q_{02}, \dots, Q_{0N})$, each value in R_0 is adjacent, and the difference is very small.

(2) Using logistic equation to calculate the initial vector R_0, a chaotic sequence $c_1, c_2, \dots c_n$ is generated. Here, after several iterations, the system will be completely chaotic. The vector layer can be expressed as:

$$c_{i+1} = c_i(1 - c_{i-1})\lambda \quad (7)$$

In the formula, λ is an iterative control parameter.

(3)Set the space particle X_i, calculate the better position of X_i, remember X_i.

$$X_i' = r \cdot rnd \cdot c_j + X_i \quad (8)$$

In the formula, r is the active radius of particle X_i, $rnd \in [-1,1], j \in [0, n]$.

The main ideas of particle swarm optimization based on chaotic mechanism are as follows: on the one hand, the position and velocity of particles are initialized by chaotic sequence, which not only keeps the diversity of particles, but also enhances the search ability of particles because of its ergodic characteristics. On the other hand, chaotic state can make the movement of particles persistent.

Particle chaos initialization: X_i in formula (8) is given initial values respectively, and the velocity in particle swarm iteration is revised again:

$$v_{i,j}^{'}(t+1) = \alpha v^{"}(t) + \beta^0(t)(x_{lb}(t) - x_{i,j}(t)) + \beta^1(t)(x_{gb}(t) - x_{i,j}(t)) \quad (9)$$

In the formula, α is a constant in the range (0,1), β is a random number with N [0,1] normal distribution, $i \in [1,n], j \in [1, m]$, n is the number of particles and m is the spatial dimension. About $v''(t)$:

$$v^{"}(t) = v_{i,j}(t) \mid \theta = 0$$
$$v^{"}(t) = N[0,1] \cdot \delta \cdot \tilde{v} \mid \theta = 1 \quad (10)$$

$$\theta = 0 \mid f(x_{gb}(t-1)) > f(x_{gb}(t))$$
$$\theta = 1 \mid f(x_{gb}(t)) = f(x_{gb}(t-1)) = \cdots = f(x_{gb}(t-5)) \quad (11)$$

In the formula, $\tilde{v} = v_{\max} \cdot c_i / 1,1$, $\delta = f(x_{gb}) - f(x_T)$, c_i is a new chaotic sequence, $f(x_{gb})$ is a satisfactory solution, $f(x_T)$ is the objective solution.

The introduction of chaotic mechanism will have a positive impact on the search process. In this paper, the chaotic sequence is proposed to replace the weight coefficient of random distribution in PSO to complete particle velocity updating.

Water volume optimization

Reasonable water distribution can ensure a reasonable temperature field under the condition of stable casting speed and control the influence of superheat in an effective range. The distribution of water volume is affected by such factors as casting speed, steel grade and slab size. The following secondary cooling control relations are obtained through analysis:

$$Q_i = A_i V^2 + B_i V + C_i + \Delta Q \quad (12)$$

In the formula, Q_i is the amount of water in each section (L / min), ΔQ is a water fine-tuning parameter, A_i, B_i, C_i is the adjustment coefficient, V is casting speed (m / min).

Based on the continuous caster of a steel plant, the design of water quantity is Table 1:

Table 1 **Contrast table of casting speed water volume**

Steel grade	casting speed / m/min)	Total water volume / L/min)
Carbon structural steel	1,7	406
	1,8	431
	2,0	479
	2,5	615

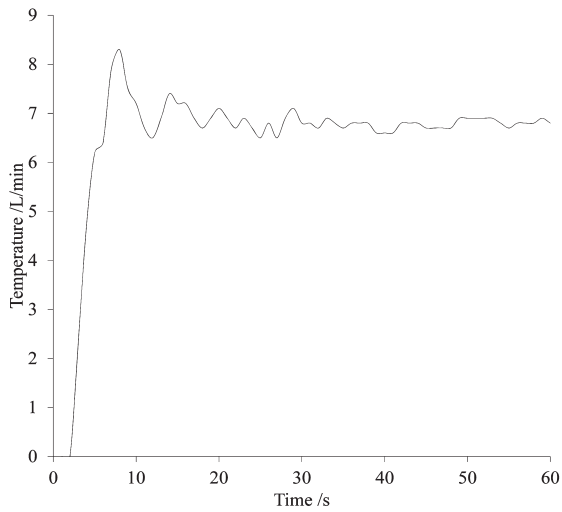
EXPERIMENTAL ANALYSIS

The outlet position of each section is selected as the control point in the water distribution control of secondary cooling zone, and the surface temperature of slab is calculated to carry out optimization analysis. The secondary cooling zone is divided into four sections with a cross section 0,15 × 0,15 m . The steel grade Q235 is selected, the specific heat capacity of solid phase is 670 $J / kg{\cdot}K$, the specific heat capacity of liquid phase is 831 $J / kg{\cdot}K$, the density of solid phase is $7{,}4\times10^3$ kg / m^3, the density of liquid phase is 7×10^3 kg / m^3, the thermal conductivity of solid phase is 29,3 $W / m{\cdot}K$, and the thermal conductivity of liquid phase is 116,6 $W / m{\cdot}K$. The casting temperature is 1550 °C and the casting speed is 2,0 m / min. Particle swarm optimization (PSO) algorithm has 400 iterations and 20 population sizes. The optimized simulation structure is shown in Table 2, Figure 1 and Figure 2.

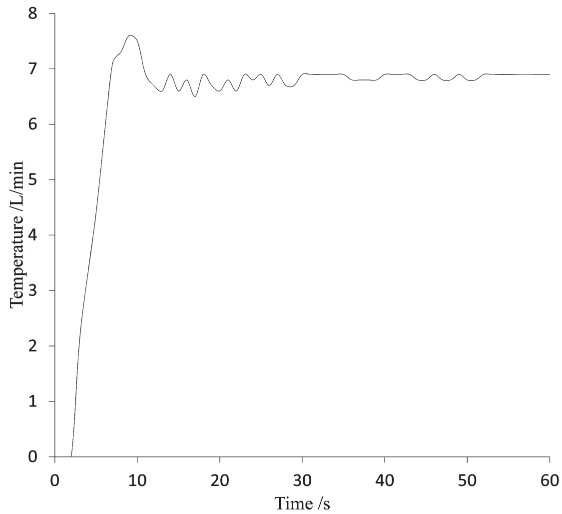
Figure 1 is the convergence analysis of the algorithm. According to the graph, the convergence speed of the improved algorithm is faster and it enters the stable period earlier. In the step water analysis of Figure 2, the jump of dynamic water distribution is smoother and more stable in the later stage. Table 2 shows that all data of slab meet the requirements. Through the comparison of the water quantity in Table 3, it is found that the optimized water quantity is obviously reduced, reaching the expectation.

CONCLUSIONS

Through intelligent optimization control of secondary cooling water distribution system, the optimization



a) Unoptimized step water flow



b) Optimized step water flow

Figure 2 Step water flow comparison

Table 2 **Slab index data under dynamic water distribution condition**

casting speed / m / min	crystallizer exit shell thickness /mm	Surface temperature of straightening point / °C	Liquid-core length of slab / m
1,7	10	902	7,03
1,8	10	909	7,47
2,0	10	918	7,91
2,5	7,5	957	10,34

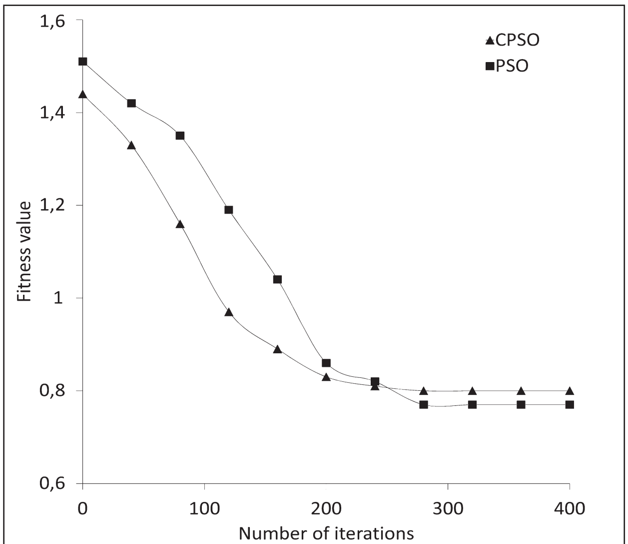


Figure 1 Convergence analysis

Table 3 **Water volume comparison before and after optimization**

casting speed	1,7	1,8	2,0	2,5
1 section	86,1	104,7	111,8	150,1
2 section	73,9	83,9	97,3	122,8
3 section	64,5	65,6	78,6	104,6
4 section	51,5	51,8	61,3	77,5

algorithm has good convergence and high accuracy. The calculation shows that the total water volume decreases obviously and the spray water volume decreases by 25 %. In the comparison of shell thickness, the error is controlled within 4 %. At the same time, the step change of water volume under different casting speeds is stable, and there is no big deviation between them.

Acknowledgments

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

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