An Optimization Control Method for Heat Transfer Model during Slab Continuous Casting

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Abstract. Solidification of continuous casting slab is a complex process including a series of phenomena such as heat transfer, mass transfer and flow. The secondary cooling process plays an important role in the production quality of continuous casting slab. In this paper, an improved particle swarm optimization algorithm has been proposed. The simulation results show that the optimized slab temperatures have more reasonable and uniform distribution. The purpose of slab quality improving is achieved and the feasibility of secondary cooling water distribution scheme is verified.

1. Introduction
With the development of high effective steel continuous casting, the process parameter analysis and optimization of secondary cooling control not only determines the productivity of caster, but also significantly impacts on slab quality[1,2]. The appropriate secondary cooling strategies are important premise and foundation in continuous casting process. The cooling practices have a considerable influence on the formation of the surface and internal quality defects which can be formed in the continuous casting production process. The slab will be cooled by a carefully designed and operated spray cooling system to improve slab quality [3]. Currently, the cooling strategies optimization of secondary cooling water distribution mainly adopts the method based on steel target temperature. Namely, under the premise of guaranteeing slab quality, the steel target temperature could be determined combining with high temperature mechanical properties experiment of the steel grade and casting equipment conditions, and then the water distribution could be obtained.

The present work proposes an improved particle swarm optimization algorithm based on mutation operator, which has the advantages of high speed convergence, strong global search capability, avoiding local optimum etc. Considering the actual casting conditions, the mutation operator particle swarm optimization (MOPSO) algorithm is put forward for optimizing slab surface temperature and secondary cooling water distribution combining with heat transfer numerical calculation. The feasibility of this algorithm is verified by simulation test results.

2. Establishment of the Mathematical Model

2.1. Modeling Conditions
The solidification process of molten steel in continuous casting machine can be regarded as the heat release and transfer process. The molten steel is impacted by the strong cooling effect in the mold and then the thin shell is formed. The thickness of slab shell is gradually increased with the spray effect of secondary cooling water. The quarter slab section is selected as the research object considering the spatial symmetry, as shown in Figure 1.
The equation of heat transfer can be given as formula (1).

$$ \rho c \frac{\partial T(x, y, t)}{\partial t} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T(x, y, t)}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T(x, y, t)}{\partial y} \right) + S $$  \hspace{1cm} (1)

where $c$ represents the specific heat of steel, J/(kg·K); $\rho$ indicates the density of steel, kg/m$^3$; $T$ is the slab instantaneous temperature, K; $\lambda$ represents the thermal conductivity, W/(m·K); $t$ is the time, s; $x$ and $y$ express the length along slab width and slab thickness separately, m; $S$ is the energy source term, W/m$^3$.

2.2. Initial and Boundary Conditions of Model
At the initial stage of liquid steel injection into the mould, it is considered that the liquid steel temperature at the meniscus of the molten steel in the mould is equal to the casting temperature $T_{\text{cast}}$, which is described as formula (2).

$$ T(x, y, t)|_{t=0} = T_{\text{cast}} $$  \hspace{1cm} (2)

In the mold, the heat flux between the molten steel and the copper plate can be expressed as the instantaneous heat flux distribution along the direction of drawing, which is described by the second kind of boundary condition as formula (3).

$$ Q = A - B \left( \frac{z}{V_{\text{cast}}} \right)^{-1} $$  \hspace{1cm} (3)

where $A$ and $B$ represent the heat flux coefficients; the mold heat flux is $Q$, W/m$^2$; $z$ is the length from meniscus, m; $V_{\text{cast}}$ is the casting speed, m/min.

The heat transfer coefficient between slab and cooling water is expressed as formula (4) after the slab leaves the mold.

$$ h_{\text{spray}} = \frac{1570.0w^{0.55}[1.0-0.0075(T_{\text{spray}}-273.15)]}{\alpha} $$  \hspace{1cm} (4)

where $T_{\text{spray}}$ expresses the cooling water temperature, K; $w$ is spray cooling water flux, L/(m$^2$·s); $\alpha$ is the caster factor; $h_{\text{spray}}$ is the heat transfer coefficient between slab and cooling water, W/(m$^2$·K).

In addition, the radiation heat transfer between the slab surface and the external environment should be considered, as shown in equation (5).

$$ h_{\text{rad}} = \varepsilon \sigma \left( T_{\text{surface}}^2 + T_{\text{ambient}}^2 \right) $$  \hspace{1cm} (5)

where $\varepsilon$ expresses the slab surface emissivity; $\sigma$ is the Stefan-Boltzman constant, W/m$^2$·K$^4$; $T_{\text{ambient}}$ and $T_{\text{surface}}$ are the ambient temperature and slab surface temperature separately, K.

3. Improved Particle Swarm Optimization Algorithm
Particle swarm optimization (PSO) is a group optimization algorithm based on stochastic optimization technology and inspired by the behaviour of birds, which is developed by Kennedy and Eberhart in 1995[4]. The individuals, named particles, are grouped into a group, which tracks the optimal particles in search space in this algorithm. Each particle is associated with a position and a velocity. Each particle
adjusts its own flight path according to its flight experience and that of its neighbours. The particle will update itself by two extreme values. One is single extreme value, called pbest which is the optimal value obtained from the particle itself search. And the other is the optimal value obtained from the whole particles, which is global extreme value, called gbest.

Because of the trend of approaching the individual previous best position and generation previous best position of particles, the PSO population presents a quick convergence effect, which easily leads to the phenomenon of local optimum, premature convergence and stagnation [5]. And the performance of PSO depends on the algorithm parameters. The introduction of mutation operator based on the genetic algorithm could keep PSO algorithm from stagnating [6]. If certain generations or the algorithm stop optimizing, the 20% particles which have the worst fitness values will be substituted. The stagnation state will be broke by mutation force, and the local optimum problem will be solved. The flow chart of mutation operator particle swarm optimization (MOPSO for short) is displayed in Fig. 2.

![Figure 2. MOPSO algorithm](image)

4. Optimization Control Results and Discussion

4.1. Main Technical Parameters

Taking the bow-type slab caster of a domestic steel plant as the research object, the equipment parameters of the caster are shown in Table 1. Taking the alloyed medium carbon steel as a research object, the relevant parameters are shown in Table 2.
**Table 1.** Caster equipment parameters

| Parameters                      | Value      |
|--------------------------------|------------|
| Caster type                    | Bow-type   |
| Tundish capacity               | 45t        |
| Caster radius                  | 10.75m     |
| Number of strands              | 1          |
| Number of secondary cooling zone| 8         |
| Number of segments             | 12         |
| Metallurgical length           | 29.34m     |
| Casting speed                  | 0.6-1.4m/min |
| Effective mold length          | 800mm      |

**Table 2.** Relevant parameters of alloyed medium carbon steel

| Parameter                        | Value          |
|----------------------------------|----------------|
| Slab width / thickness           | 2265/220 mm    |
| Superheat                        | 30 °C          |
| Liquidus temperature             | 1512.1 °C      |
| Solidus temperature              | 1445 °C        |
| Latent heat                      | 274950J/kg     |
| Density of steel                 | 7200kg/m³      |
| Spray water temperature          | 30 °C          |
| Ambient temperature              | 35 °C          |

4.2. Secondary Cooling Technology Optimization Based on MOPSO

Fig. 3 depicts comparison of optimization results for slab surface temperature along the casting direction. While the surface temperature comparison between before and after optimization along the broad face center axis of strand, as well as the target temperature, is shown in Table 3. Apparently, after the optimization based on metallurgy criteria, the slab surface temperature is closer to the target temperature. The optimized surface temperature has a more proper and uniform distribution. The slab surface temperature at the exit of caster is increased effectively, which ensures the slab quality and rolling requirement.

![Figure 3. Slab surface temperature comparison between before and after optimization](image)
Table 3. Comparison between before and after optimization of partial secondary cooling scheme

| Secondary cooling zone | Target temperature | Before optimization | After optimization |
|------------------------|--------------------|---------------------|--------------------|
| 2#                     | 1010°C             | 973.4°C             | 980.0°C            |
| 4#                     | 975°C              | 967.4°C             | 972.5°C            |
| 7#                     | 920°C              | 918.1°C             | 919.6°C            |

5. Conclusions
The paper puts forward an optimization method of secondary cooling water distribution for steel continuous casting based on improved particle swarm optimization algorithm with mutation operator. The slab surface temperature at the exit of caster is improved effectively and the slab surface temperature is closer to target temperature with more reasonable and uniform distribution after the optimization.

6. References
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