Research on Solve of Heat Transfer Coefficients and Experimental of the Heavy Plate in laminar cooling process

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Abstract. Heat transfer model is the premise of adjusting cooling control strategy in laminar cooling process. The accuracy of heat transfer coefficient directly affects the accuracy of the temperature model. However the accuracy of heat transfer coefficient is difficult to determine. In this paper, the model of heat transfer coefficient is solved by using chaos particle swarm optimization algorithm. The experimental system was designed and the temperature drop of the points in the plate was measured in laminar cooling process. Compared with the experimental results, the average error of the measurement points is 5.2°C, and the standard uncertainty is 1.4°C. It is proved that the calculation method of heat transfer coefficient is better than empirical formula at the same cooling condition.

1. Introduction

The purpose of controlled cooling is to adjust the austenite structure and refine grain structure, improving the metallographic structure and mechanical properties of billets. Therefore, it is necessary to understand the current temperature distribution so that change the grain structure by adjusting the control strategy [1, 2]. Moreover, with the improvement of control accuracy, the accuracy of temperature model has become an important factor affecting the accuracy of control cooling strategy.

The surface heat transfer coefficient is an important but unmeasurable parameter in the heat transfer model. Its accuracy directly affects the accuracy of the heat transfer model. However, there is a great difference in the heat transfer coefficient under different cooling conditions [3]. The heat transfer coefficient is related to the water flow density, cooling water temperature, roll speed and other parameters. The factors are complex and interconnection. Many scholars get the heat transfer coefficient by empirical formula or data regression [4, 5]. Due to different conditions on site, the empirical formulas also varies greatly because of different equipment in laminar cooling process. The accuracy of empirical formulas cannot be guaranteed. The research on the surface heat transfer coefficient is the difficulty and a hot spot of establishing the temperature model.

In this paper, a method to solve the heat transfer coefficient is proposed: chaos particle swarm optimization algorithm is used to establish the inverse heat transfer problem model, and the heat transfer coefficient of the upper and lower surfaces of the plate is solved based on the measured data by experiments and the inverse heat transfer problem model. On the laminar cooling platform, an experimental system is built to measure the temperature of three points in the plate, which is used as the input of the inverse problem model to calculate the heat transfer coefficient. The solved results of heat
transfer model are compared with the experimental data, its shows the accuracy of the proposed method.

2. Establishment of heat transfer coefficient model based on Chaos Particle Swarm Optimization

2.1 The Solution method of heat transfer coefficient model

We obtain the temperature data of some points inside the plate by experimental measurement, and solve the boundary conditions or physical parameters by numerical solution equation. It is the inverse heat conduction problem [6, 7]. The solution of heat transfer coefficient belongs to the inverse problem of heat conduction.

![Diagram of heat transfer coefficient model](image)

Figure 1. The calculation principle of heat transfer coefficient model.

Fig. 1 shows the calculation principle of heat transfer coefficient model. Firstly, the data of three temperature points in the plate were measured by laminar cooling experiment. Then the heat transfer model is established at the same cooling condition, and an initial heat transfer coefficient is set up. Through continuous adjustment of heat transfer coefficient, the error between the measured temperatures and the calculated temperatures become small enough. At this time, it shows the accuracy of heat transfer coefficient.

The adjustment of heat transfer coefficient usually adopts empirical formula. Many empirical formulas of heat transfer coefficient are quite different due to different equipment on site. Based on the previous experience [8], the water-cooled heat transfer coefficient model selected is as follows:

$$h = aw^b e^{-ct}.$$  

(1)

Where, $w$ is the cooling water flow; $T$ is the current temperature of plate; $a, b, c$ are the parameters to be identified.

Formula 2 is the objective function to be optimized.

$$\min J(h) = \sum_{i=1}^{m} [T_i^f(h) - T_i^m]^2.$$  

(2)

Where, $h$ is the amount to be retrieved, $m$ is the length of measurement sequence, $T_i^f$ is the calculated temperature, and $T_i^m$ is the measuring temperature.

Because the temperature gradient in the thickness direction is much larger than the width and length direction, heat transfer model only considers the thickness direction. Considering the asymmetry of the upper and lower surfaces in cooling process, the heat transfer coefficients of the upper and lower surfaces
are calculated respectively, and the boundary conditions are as follows:

\[-\lambda \frac{\partial T}{\partial x} = h_u (T - T_\infty) .
\]
\[\left(3\right)\]

\[-\lambda \frac{\partial T}{\partial x} = h_l (T - T_\infty) .
\]
\[\left(4\right)\]

Where, \(h_u\) and \(h_l\) are the heat transfer coefficients of the upper and lower surfaces respectively; \(x\) is the thickness direction, \(x = 0\) is the upper surface, \(x = L\) is the lower surface; \(\lambda\) is the thermal conductivity; \(T_\infty\) is the ambient temperature.

2.2 Chaos particle swarm optimization

For the unknown parameters in the heat transfer coefficient, it belongs to the multi-dimensional continuous variable optimization problem. Particle swarm optimization (PSO) does not need to solve the spatial gradient, which is suitable for solving such complex combined optimization problems. The principle of parameter identification is simple and realizable [9].

In algorithm, each heat transfer coefficient value is called "particle". The particles constantly updates "position" and "speed" to approach the optimal solution. The update expression of particle speed and position is as follows:

\[v_i^d(t + 1) = w v_i^d(t) + c_1 r_1 (p_i^d - x_i^d(t)) + c_2 r_2 (p_i^d - x_i^d(t)) .
\]
\[\left(5\right)\]

\[x_i^d(t + 1) = x_i^d(t) + v_i^d(t + 1) .
\]
\[\left(6\right)\]

Where, \(c_1\) and \(c_2\) are non-negative acceleration constants, and they are usually between \([0, 2]\), \(r_1\) and \(r_2\) are random distributed in \([0, 1]\), \(t\) is the current iteration number, and \(w\) is the inertia weight.

In this paper, \(w = 0.9\), \(c_1 = c_2 = 2\). The initial particles are generated randomly according to uniform distribution in the feasible region.

When some particles are close to the group optimal solution, the evolution of particles slow down and they tend to fall into local optimal solution. In order to make particles jump out of the state, chaos mechanism is introduced to update particles. When the continuous \(N\) times of particle \(i\) satisfies \(|f_{i(t)} - f_{i(p)}| < \delta\) (\(f_{i(t)}\) is adaptive function), the effective radius of the particle \(i\) is enlarged

\[x_{i,d}^d(t + 1) = x_{i,d}^d(t) + R_y^d (2y_i^d - 1) .
\]
\[\left(7\right)\]

Where, \(y_{(k,d)}\) is generated by logistic map iteration:

\[y_{k+1,d} = 4y_{k,d} (1 - y_{k,d}) .
\]
\[\left(8\right)\]

Where, the initial \(y_0\) is randomly generated according to the uniform distribution at \((0, 1)\).

3. The experiment of temperature measurement in laminar cooling process

The purpose of the experiment is to obtain the temperature data of the plate during the cooling process, and providing the input data for heat transfer coefficient model. The surface heat transfer coefficient is calculated indirectly by using the calculated temperature and the measured temperature of the internal measuring point.

Fig. 2 shows the laminar cooling platform. The plate was heated to 800°C and adequate insulation. Taking out the sample and insert the thermocouple into the measuring hole. The sample is placed on the laminar cooling platform and collecting temperature data. Recording the temperature data under different experimental conditions: 400 L/min·m², 700 L/min·m² and 1000 L/min·m², and the cooling time: 10 s and 20 s.
Figure 2. The laminar cooling platform and the temperature measurement process.

Fig. 3 shows a sample with a waterproof edge and asbestos insulation at sides. Three measuring points are selected. Two measuring points close to the upper and lower surfaces are 3mm away from the surface. The closer the distance is, the more sensitive the temperature changes and the more accurate the measurement are.

The advantage of the edge to reduce the possibility of cooling water flowing into the temperature hole and improving the accuracy of measurement. Because the paper studies the heat transfer in thickness, adiabatic treatment is carried out in the direction of length and width. An adiabatic asbestos groove is added to the side of the sample, so that only the upper and lower surfaces are heat exchanged.

Figure 3. The sample with a waterproof edge and asbestos groove.

In this paper, K-type thermocouple is selected to measure the temperature. Data acquisition uses Advantech ADAM-4018 module, and upper computer uses VB programming to collect data and temperature compensation. Fig. 4 shows the measurement system of the cooling experiment.

Figure 4. The data acquisition system of cooling experiment.

4. The result and analysis of heat transfer coefficient

4.1 The identification result of parameters in heat transfer coefficient model

The model parameters $a$, $b$, $c$ are identified by chaos particle swarm optimization algorithm, and table 1 shows the parameters value of the upper and lower surface. The heat transfer efficiency of the upper surface is obviously higher than the lower surface.
Table 1. the model parameters of heat transfer coefficient

| Surface      | Parameters | a    | b    | c     |
|--------------|------------|------|------|-------|
| upper surface|            | 2892 | 1.00311 | 0.008268 |
| lower surface|            | 3002 | 0.74768 | 0.005766 |

Fig. 5 shows the relationship between the heat transfer coefficient and the surface temperature at different water flow densities. At the initial of cooling, the surface heat transfer coefficient is small, and the plate surface is in the "film boiling" state. With the heat loss of surface, the water film is broken to the "nuclear boiling" state, and the heat transfer coefficient rises rapidly.

Figure 5. The Heat transfer coefficient under different flow densities.

4.2 Comparative analysis of model accuracy
The identification parameters are substituted into the heat transfer coefficient. And then the heat transfer coefficient is substituted into the heat transfer model, so the calculated value of temperature field is obtained at the same cooling condition. In order to verify the accuracy of the identifying method for the heat transfer coefficient, the calculated results of three measuring points are compared with the experimental results. The maximum error is less than 7.7 ℃, and the standard uncertainty is less than 1.4 ℃.

The same method is used to identify the parameters of air cooling stage and red returning stage, drawing the curves of calculated and experimental results of two measuring points. As shown in Fig. 6, the calculated results are basically consistent with the experimental results. "Upper point" is the point close to the upper surface in the three measuring points, and "lower point" is close to the lower surface of the plate.

Figure 6. The calculated and measured curve of cooling process.
5. Conclusion
In this paper, chaos particle swarm optimization is proposed to solve the heat transfer coefficient. According to the obtained parameters of heat transfer coefficient, the temperature distribution of plate is calculated in the same cooling condition. The experimental system is established for measuring the internal temperature of plate, and the temperature data is collected in the laminar cooling platform.

In order to verify the accuracy of the calculation of heat transfer coefficient, the calculated results and measured results of the same measuring point are compared. The average error is 5.2 °C, and the standard uncertainty is 1.4 °C. It is better than the error based on the empirical formula, which proves the accuracy of the method.

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References
[1] H. Xie, Z. Jiang, X. Liu, “Prediction of cooling temperature on run-out table of hot strip mill using data mining,” Journal of Materials Processing Technology, vol. 77, no. 3, 2006, pp. 121-125.
[2] Y. Lee, S. Choi, D. Hodgson, “Integrated model for thermo-mechanical controlled process in red (orbar) rolling,” Journal of Materials Processing Technology, vol. 65, no. 2, 2002, pp. 678-688.
[3] S. Ahmad, H. Saeid, “Simulation-based prediction of hot-rolled coil forced cooling,” Applied Thermal Engineering, vol. 28, no. 13, 2008, pp. 1630-1637.
[4] P. Wang, Z. Hu, Z. Xie, and M. Yan, “A new experimental apparatus for emissivity measurements of steel and the application of multi-wavelength thermometry to continuous casting billets,” Review of Scientific instruments, vol. 89, 2018, pp. 054903.
[5] E. Sheila, S. Ahmad, H. Saeid, “Effect of phase transformation latent heat on prediction accuracy of strip laminar cooling,” Journal of Materials Processing Technology, vol. 21, no. 3, 2011, pp. 1776-1784.
[6] K. Hamed, K. Farshad, “Solution of inverse heat conduction problem using the lattice boltzmann method,” International Journal of Heat and Mass Transfer, vol. 39, no. 6, 2012, pp. 1410-1417.
[7] M. Samai, T.Loulou, “A comparative study of heat flux and temperature based objective functional to solve inverse heat conduction problems,” Numerical Heat Transfer, vol. 28, no. 1, 2009, pp. 75-101.
[8] W.Zima, J. Taler, “Solution of heat conduction problems using control volume approach,” International Journal of Heat and Mass Transfer, vol. 23, no. 6, 1999, pp. 1123-1140.
[9] C. Dong, G. F. Wang, Z. Y. Chen, “A method of self-adaptive inertia weight for PSO,” International Conference on Computer Science and Software Engineering, 2008, pp. 1195-1198.