Applied Thermal Engineering 114 (2017) 36–43

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

# Identification of heat transfer coefficients of steel billet in continuous casting by weight least square and improved difference evolution method

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## HIGHLIGHTS

- An integrated approach for obtaining heat transfer coefficients is presented.
- This approach is constructed by weight least square and improved difference evolution method.
- SAE 1007 billet is used to illustrate the validity of this approach.
- The corrected heat transfer model is obtained.
- Predicted results are confirmed by the actual industrial data.

## ARTICLE INFO

*Article history:*
Received 14 July 2016
Revised 19 November 2016
Accepted 24 November 2016
Available online 25 November 2016

*Keywords:*
Secondary cooling zone
Heat transfer coefficient
Liquid pool length
Difference evolution algorithm
Weight least square

## ABSTRACT

The surface heat transfer coefficients of steel billet play very important roles in the accurate heat transfer model. However, these heat transfer coefficients are difficult to be fixed. The main work of this paper focuses on identifying these heat transfer coefficients by solving the inverse heat transfer problem. In order to estimate these heat transfer coefficients better, this paper presents an improved difference evolution algorithm. The SAE1007 steel billet is used to conform the validity of this algorithm. With the help of the surface temperature measurement, this algorithm can identify these heat transfer coefficients effectively. Comparing with the difference evolution algorithm, this improved algorithm can reduce iterative number and has better convergence. Due to the horrible production environment, there are some outliers in the measured values. To eliminate these outliers, the weight least square method is also introduced. Finally, the corrected heat transfer coefficients are used to enhance the accuracy of the heat transfer model, which is applied to predict the solidified shell thickness of steel billet. The predicted results are confirmed by the actual industrial data.



## 1. Introduction

The production of steel billet is finished by the continuous caster. A brief description of the continuous casting process is shown in Fig. 1. Since many technical requirements should be taken into consideration in this process, it is necessary to build a heat transfer model, which can be used to analyze some phenomena and processes successfully. Therefore, the accuracy of mathematical model of steel billet becomes very crucial, the surface heat transfer coefficients of which are the key factors, and these coefficients are difficult to be fixed.

In many research works, the heat transfer coefficients are determined through the lab trials [1–3]. These cannot be used directly in the industry spot according to literature [4], due to the existence of the deviation between the actual casting process and the experimental environment. For this reason, many literatures [5,6] discuss the identification of heat transfer coefficients in the heat transfer model, which belongs to inverse heat conduction problems (IHCP). Huang and Wang [7] solved a three-dimensional (3-D) transient inverse heat conduction problem by the conjugate gradient method (CGM), and in 2005 they [8] estimated the surface heat transfer coefficients by solving the three-dimensional inverse heat conduction problem. Chen et al. [9] evaluated the unknown heat flux and temperature on the external surface of the circular pipe by solving IHCP. Wikström et al. [10] solved the IHCP by the Fourier transform method. Le Bideau et al. [11] evaluated the heat

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http://dx.doi.org/10.1016/j.applthermaleng.2016.11.173
1359-4311/

**Nomenclature**

| | |
|---|---|
| $T$ | temperature (K) |
| $\rho(T)$ | density (kg/m$^3$) |
| $\lambda(T)$ | thermal conductivity (W/(m K)) |
| $\lambda_l$ | liquid thermal conductivity coefficient (W/(m K)) |
| $\lambda_s$ | solid thermal conductivity coefficient (W/(m K)) |
| $m$ | a factor |
| $f_s$ | solid fraction |
| $t$ | time (s) |
| $Q(T)$ | internal heat generation |
| $L$ | latent heat of fusion (J/kg) |
| $T_{cast}$ | pouring temperature (K) |
| $q$ | mold heat flux (W/m$^2$) |
| $A$ and $B$ | parameters calculated by engineering experiment measurements |
| $T_w$ | spray cooling water temperature (K) |
| $h_i$ | heat transfer coefficient in the $i$th zone (W/(m$^2$ K)) |
| $\triangle x$ and $\triangle y$ | distance between element central points |
| $w_{min,j}$ and $w_{max,j}$ | the lower and upper bounds of $j$th decision parameter |
| $D$ | the number of decision parameter |
| $F$ | a constant of DE |
| $CR$ | crossover rate |
| $f(h)$ | a fitness value |
| $N$ | number of measuring position |
| $T_{ic}$ | the calculated value of slab surface temperature |
| $T_{ie}$ | the measured value of slab surface temperature |
| $NM$ | population |
| $T_M$ | real values |
| $T_M^{\delta}$ | the surface temperature measurements with relative error level ($\delta$) |
| $v_i$ | the weight in the new fitness function |
| $f_{New}$ | a new fitness value |
| $\xi_i$ | residuals |
| $G$ | standard deviation of the residuals |
| $\phi$ | kernel function |
| $y$ | an independent variable |
| $\widetilde{\omega}$ | the corresponding weight percentage |

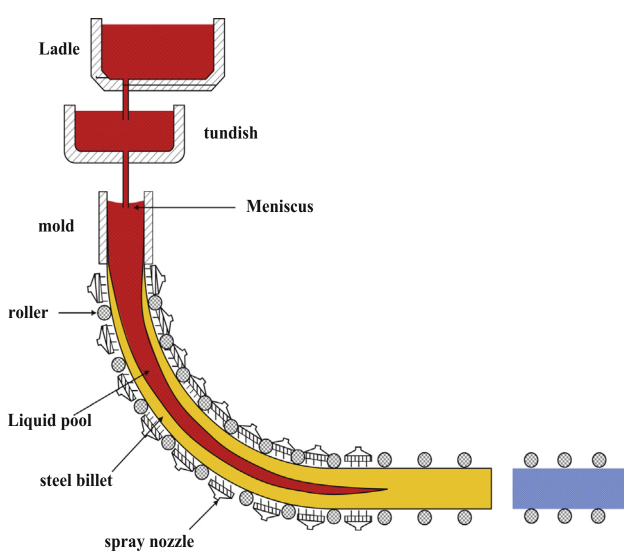


**Fig. 1.** Schematic diagram of continuous casting machine.

flux in an infrared experimental furnace. Lu et al. [12] estimated the fluid temperature by solving the two-dimensional IHCP in a pipeline. Cui et al. [13] used least square method to solve the transient heat flux. Lu et al. [14] identified the heat convection coefficient, fluid temperature and wall temperature on the inner wall of a pipeline. Recently, some authors study the IHCP in the process of continuous casting. Carlos et al. [15] evaluated the surface heat transfer coefficients of steel billet by the inverse method. Slota [16] identified the cooling condition in 2-D and 3-D continuous casting process by solving the inverse Stefan problem. Yang et al. [4] identified the heat transfer coefficients by chaos particle swarm optimization (PSO) algorithm. At the same time, Wang et al. [17] obtained the heat transfer coefficients by solving the IHCP and the results were compared with the pin-shooting experimental values. Because IHCP needs huge iterations and is very sensitive to the measured errors, Wang et al. [18] use the PSO algorithm to optimize the heat transfer coefficients. However, PSO algorithm is easy to trap into a non-optimal "local minimum". Based on the above reasons and our previous work [19], this paper presents an improved differential evolution (IDE) algorithm. Since the measured values of surface temperature are often contaminated by the noise, this paper combines the weighted least square and improved differential evolution (WLS-IDE) algorithm to estimate the heat transfer coefficients.

The structure of this paper is constituted as follows. In Section 2, heat transfer model of steel billet is given. DE and IDE algorithms are introduced in Section 3 and the simulation is used to conform this method. In Section 4, WLS-IDE algorithm is developed and the simulation is used to illustrate the validity of this method. The corrected heat transfer model is used to predict the shell thickness of slab in Section 5. In Section 6, the summary of this paper is described.

## 2. Mathematical model and boundary conditions

### 2.1. Mathematical model

In the productive process of steel billet, if the mathematical model is established on basis of the actual situation completely, the solving process of this model will become complex and difficult. In this paper, the mathematical model of steel billet is considered to be used in control system, which needs to ensure the real-time capability. If this model is too complex, the solving time will become longer. Therefore, some assumptions should be given and the heat transfer model of steel billet in Fig. 2 is based on some reasonable assumptions [4,15]:

(1) Convective heat transfer is equivalent to the thermal conduction in the process of continuous casting; (2) the meniscus surface is considered to be flat; (3) the latent heat of solidification in the mushy zone is converted into the equivalent specific heat capacity; (4) the influence of gravity and geometry is neglected; (5) the heat transfer at the direction of casting can be ignored. According to the above assumptions, the heat transfer model [15,17] is given by

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