International Journal of Heat and Mass Transfer 90 (2015) 645–653

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Estimation of heat transfer coefficients and heat flux on the billet surface by an integrated approach

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ARTICLE INFO

Article history:
Received 8 February 2015
Received in revised form 19 May 2015
Accepted 2 July 2015

Keywords:
Heat transfer coefficient
Secondary cooling zone
Levenberg–Marquardt algorithm
Nonlinear inverse heat transfer problem
Shell thickness of billet

ABSTRACT

The heat transfer coefficients and heat flux of the billet surface in continuous casting are difficult to be measured directly by hardware measurement. Therefore, the integrated approach which combines the online temperature detection with heat transfer model of inverse problem for estimating the heat transfer coefficients and heat flux is proposed. However, the inverse problem is ill-posed and the online temperature detection is often contaminated by the error. So this paper presents the modified L–M algorithm to solve the nonlinear inverse heat transfer problem. Moreover, the SAE 1007 billet is used to illustrate the validity of this integrated approach. The heat transfer coefficients and heat flux of the billet surface are estimated and the calculated values match very well with the measured values of the billet surface temperature. The experiment results show that the modified L–M algorithm not only reduces calculated amount, but also overcomes the influence of measurement error on the inverse results. Finally, the corrected heat transfer coefficients are used to improve the accuracy of the heat transfer model, which can be applied to predict the solidified shell thickness of billet, and the predicted results are confirmed by the actual industrial data.

1. Introduction

The continuous casting is the main solidification process of molten steel. This is a process of heat transfer between the metal and cooling zones. The cooling methods have significant influence on the formation of internal and surface defects of billets. In order to guarantee defect-free products, a well-designed and operator spray cooling system is considered. Secondary cooling control model based on the heat transfer equation has been widely used. In 1993, Louhenkilpi et al. [1] introduced a real-time heat transfer model and considered the model accuracy. Hardin et al. [2], in 2003, a two-dimensional heat-transfer model is presented to realize the control of continuous steel slab caster. Petrus etc [3] established one-dimensional finite-difference model with a decentralized controller configuration in 2011. In 2013, Ke etc [4] proposed real-time slab quality diagnosis and analysis system which was based on heat transfer model. Hence accurate heat transfer model is crucial to continuous casting steel production. Heat transfer coefficients are essential to the accurate heat transfer model. In many research works, heat transfer coefficients were determined by the lab trials [5–9]. These results may include many unsatisfied factors. Firstly, the slab surface temperature, the cooling water volume, spray coverage area and nozzle type may influence the results. Secondly, a certain discrepancy for the heat transfer coefficients may be existence, owing to long cycle term and the existence of the deviation between experimental situation and actual casting process. This discrepancy can bring serious impact on the calculation accuracy. Thirdly, the necessary instruments in the laboratory may cost too much to finish measuring the heat transfer coefficient. Recently, some research works obtained heat transfer coefficients by using the surface temperature measurements. In 2006, Carlos etc [10] quantified heat transfer coefficients based on the solution of the inverse heat transfer problem by using industrial measured billet surface temperatures. In 2014, Yang etc [11] identified the physical parameters and heat transfer coefficients by chaos particle swarm optimization algorithm. At the same time, Wang etc [12] determined the heat transfer coefficients by solving the inverse heat transfer problem and validated effectiveness of this method by using the pin-shooting experiment. However, these research works did not consider the effect of surface temperature measurement error on the inverse results. Therefore, this paper presents an integrated approach of overcoming error disturbances which assembles the online temperature measurement and heat transfer model to identify heat transfer coefficients by solving the nonlinear inverse heat transfer problem.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.07.008
0017-9310/© 2015 Published by Elsevier Ltd.

In practice, nonlinear inverse heat transfer problem [13,14] is ill-posed. That is to say, the surface temperature measurements with small error can create large disturbance in the results. The classical Levenberg–Marquardt (LM) [15–18] algorithm is a valid method for solving this nonlinear inverse heat transfer problem. Recently, many research works [19–21] focus on improving this algorithm with non-exact line search. These works are seldom used in industry engineering because the non-exact line search needs to calculate the inequality continually until the condition is satisfied, which may increase the amount of calculation, especially for heat transfer model in continuous casting. In order to overcome this problem, this paper presents a modified Levenberg–Marquardt (MLM) algorithm with the exact linear search to estimate the heat transfer coefficients. The convergence of MLM algorithm is analyzed. By the actual measured data, the heat transfer coefficients are obtained and the results match with the measured data very well. At last, the measured data with error are used to estimate the heat transfer coefficients. Simulation experiment illustrates this integrated approach of overcoming error disturbances can overcome the error effectively.

2. Mathematical model of solidification heat transfer

In process of the continuous casting, the three-dimensional steady state heat transfer model is obtained from literature [22]:

$$\rho(T)c(T)V_{cast}\frac{\partial T}{\partial z} = \nabla(k(T)\nabla T) + Q(T). \tag{1}$$

Assuming that [23–26]: (1) the discussion focuses on two-dimensional heat transfer model in literature [26]; (2) A pseudo-steady temperature field which is occurred during the undisturbed operational cycle of the casting device (Fig. 1) is considered; (3) since the release of heat is small compared to that in the cross directions, it can be ignored in the casting direction; (4) the mold is considered uniformly and the initial temperature is equal to the water-cooling temperature (T_w); (5) the meniscus surface is considered to be flat.

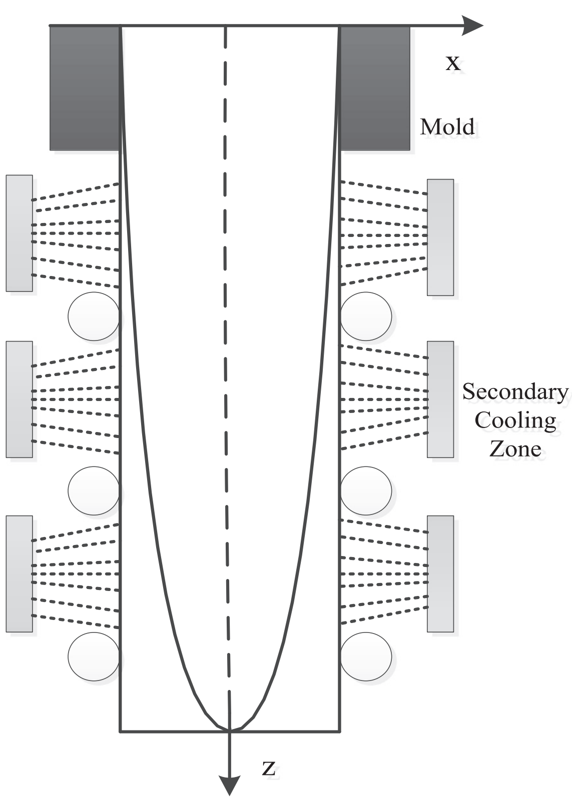

Fig. 1. Schematic diagram of billet [27].

Based on the above assumptions and according to the literature [26], we have the following two-dimensional heat transfer model:

$$\rho(T)c(T)V_{cast}\frac{\partial T}{\partial z} = \frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right) + Q(T), \tag{2}$$

where $\rho(T)$ is density (kg/m^3), $c(T)$ is specific heat (J/(kg · K)), V_{cast} is casting speed (m/min), $k(T)$ is the effective thermal conductivity [11] (W/(m K)), from literature [11], $k(T)$ is calculated by:

$$k = f_s k_s + m(1 - f_s)k_l, \tag{3}$$

where k_s and k_l are solid and liquid thermal conductivity coefficients respectively, m is a parameter [11]. T is temperature (K), f_s is the solid fraction and it is varying only with temperature T, t is time (s) and $Q(T)$ is the term which is associated with the internal heat generation because of the phase change. In the paper, this term is replaced by an equivalent specific heat capacity. And we can obtain

$$c_{eff} = c - L(\partial f_s/\partial T), \tag{4}$$

where L is the latent heat of fusion (J/kg) and $L(\partial f_s/\partial T)$ is pseudo-specific heat.

The initial condition is:

$$T_{begin} = T_{cast}, \tag{5}$$

T_{cast} is the pouring temperature.

According to the literature [10], the boundary conditions in the mold, SCZ and air cooling zone can be written as:

$$-k\frac{\partial T}{\partial x} = q, \tag{6}$$

q is the heat flux, and we can obtain it by the following equation:

$$q = h(T - T_w), \tag{7}$$

where $h = (h_{mold}, h_s, h_e)$, h_{mold} denotes the transient metal/mold heat transfer coefficient, h_s denotes the metal/sprays heat transfer coefficient and h_e denotes metal/environment heat transfer coefficient. From this equation, we can see that the heat flux q can be calculated according to the heat transfer coefficients h. Thus the work of this paper focuses on the estimating of the heat transfer coefficients h.

3. Identification of heat transfer coefficients based on the MLM algorithm

We define that $T_c(h,t)$ is the calculated value of the billet surface temperature, $T_e^{\delta}(t)$ is the experiment value of the billet surface temperature with error level δ. Because $T_c(h,t)$ is dependent on the heat transfer coefficients h, so the process of solving the heat transfer coefficients h can be transformed into solving the following nonlinear operator:

$$J(h) = T_c(h,t) - T_e^{\delta}(t), \quad t \in [0, t_m], \tag{8}$$

where t_m is the time when the billet in continuous casting machine. However, solving the heat transfer coefficients h also can be converted into the following equivalent optimization problem

$$\min\ G(h) = \min\left\{\frac{1}{2}\int_0^{t_m} \|J(h)\|^2 dt\right\}, \tag{9}$$

then solving the optimum of Eq. (9) can be described as solving the following equation

$$\nabla G(h) = J(h)\nabla J(h) = 0. \tag{10}$$