Journal of Materials Processing Technology 214 (2014) 44–49

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Inverse problem-coupled heat transfer model for steel continuous casting

Zhaofeng Wang[a,b], Man Yao[b], Xudong Wang[b,*], Xiaobing Zhang[c], Longsheng Yang[c], Hongzhou Lu[c], Xiong Wang[c]

[a] Faculty of Electronic Information and Electrical Engineering, Dalian University of Technology, Linggong Road 2#, Dalian, CN 116024, China
[b] School of Materials Science and Engineering, Dalian University of Technology, Linggong Road 2#, Dalian, CN 116024, China
[c] Jiangsu Shagang Group, Zhangjiagang, CN 215625, China

ARTICLE INFO

Article history:
Received 25 December 2012
Received in revised form 22 July 2013
Accepted 24 July 2013
Available online 3 August 2013

Keywords:
Heat transfer coefficient
Secondary cooling
Inverse problem
Continuous casting

ABSTRACT

An integrated approach was proposed for determining the heat transfer coefficient, which combined inverse heat transfer calculation model with temperature measurement and pin-shooting experiment. Based on the roller-layout and spray nozzle distribution, the IHTP (inverse heat transfer problem) model was developed to calculate the secondary cooling heat transfer by means of non-linear estimate method. The method transformed the inverse problem of parameter identification into solution of optimization problem using evolutionary algorithm. With the help of temperature measurement and pin-shooting experiment, the whole procedure of the model solution for identification and application in continuous casting process was given. Simulation and experiment results in plant trial confirmed the efficiency of the method used.

1. Introduction

The cooling practices in the secondary and machine cooling areas have a considerable influence on the formation of the surface and internal defects of slabs. To ensure defect-free products, the strand is to be cooled down by a well-designed and operated spray cooling system. Dynamic secondary cooling control model based on heat transfer equation has been widely used in real-time regulation of water volume, and carried out the PID adjustment through periodically comparing calculated with target slab surface temperature. The unsteady state model was dominated over the real time computation in dynamic secondary cooling. Louhenkilpi et al. (1993) developed a real-time heat transfer model and discussed the model accuracy in comparison with measured results. Hardin et al. (2003) built a two-dimensional heat-transfer model for transient simulation and realized the control of continuous steel slab caster. Petrus et al. (2011) established one-dimensional finite-difference model with a decentralized controller configuration. During the process in online calculation for strand thermal behavior mentioned above, the heat transfer coefficient played an important role on the model computation accuracy.

Mizikar (1970) and Muller and Jeschar (1973) measured the heat transfer coefficient under offline conditions in the laboratory. The results indicated that heat transfer coefficient could be influenced by many factors, including the cooling water volume, nozzle type, spray coverage area, and the slab surface temperature, etc. Due to the high cost, long cycle term and the existence of the deviation between experimental situation and actual casting process, there was a certain discrepancy for the heat transfer coefficient, which definitely brought serious impact on the calculation accuracy then resulting in improper real-time control of cooling water and causing various slab defects. Hence, it became an important and concerned theme to identify the heat transfer coefficient accurately and conveniently.

Aiming to solve the problem, the present work put forwards a novel method which coupled temperature measurement and pin-shooting experiment to estimate the heat transfer coefficient. A heat transfer and solidification mathematical model was established on account of the roller-layout and spray nozzle distribution for slab continuous caster. On the basis of this, nonlinear estimation method was adopted to calculate the heat transfer coefficient from measured surface temperature and pin-shooting experiments, and the results validated the effectiveness of the proposed method.

2. Model description

2.1. Mathematical model

The solidification of liquid steel in a caster could be considered as the releasing and transferring process of heat energy. In

* Corresponding author. Tel.: +86 0411 84707347; fax: +86 0411 84709284.
E-mail addresses: hler@dlut.edu.cn, wangzhaofeng0412@126.com (X. Wang).

0924-0136/$ – see front matter.
http://dx.doi.org/10.1016/j.jmatprotec.2013.07.017

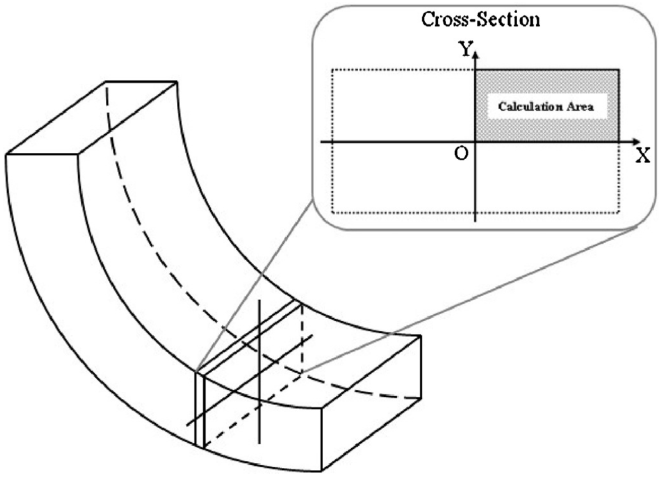

Fig. 1. Schematic diagram of the calculation domain.

the mold, liquid steel formed a shell with certain thickness and strength being suffered from the impact of intense cooling effect. On entering into the secondary cooling zone, with the acceleration of the internal heat energy transformation by spraying water, the thickness of the shell kept increasing until the slab solidified completely. In view of the spatial symmetry, the temperature profile needed to be calculated for one quarter of slab cross-section as shown in Fig. 1.

Some reasonable assumptions had been made according to the continuous casting condition by Toledo et al. (1993) and Hardin et al. (2003), which are shown as follows:

(a) The heat transfer along casting direction is ignored, and the mathematical model is translated into a two-dimensional unsteady state problem.
(b) The size variety of slab caused by solidification and shrinkage is ignored.
(c) The steel density is constant, but the specific heat capacity and heat conductivity of steel are temperature-dependent.
(d) The latent heat of steel solidification is converted into an equivalent specific heat capacity in the mushy zone.

According to above assumptions, the two-dimensional unsteady state equation of heat transfer can be given as follows:

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

where ρ is steel density, kg/m^3; c is specific heat of steel, J/(kg K); T represents the slab instantaneous temperature, K; t is time, s; λ is thermal conductivity, W/(m K); x and y represent the directions along slab width and slab thickness respectively, m; S is energy source term, W/m^3. The equivalent specific heat method is adopted to calculate the latent heat of steel, which transforms the influence of latent heat to specific heat. The formula is expressed as follows proposed by Thomas et al. (1984):

$$C_{eff} = C_p + \frac{L_H}{T_l - T_s} \quad (T_s \le T \le T_l) \quad (2)$$

where C_{eff} represents equivalent specific heat, J/(kg K); C_p represents the specific heat of steel; L_H is the latent heat of solidification, J/kg; T_l represents the liquidus temperature of steel, K; T_s represents the solidus temperature of steel, K.

Considering the effect of convection on heat transfer process within the liquid core and mushy zone, the thermal conductivity is given as an effective value by Ha et al. (2001):

$$\lambda_{eff} = \lambda_{sol}(1 + 6f_l) \quad (3)$$

where λ_{sol} is thermal conductivity of solid steel, f_l is the liquid fraction.

2.2. Initial and boundary conditions

In order to solve the heat transfer equation (1), the initial and boundary conditions must be known. To simulate the heat removal, the actual water flows in each secondary cooling loop, the cooling water volume in the mold and thermal radiation have to be considered.

2.2.1. Initial conditions

At the beginning of the continuous casting, the liquid surface at the top of mold is the upper boundary of the calculation domain. The casting temperature T_{cast} is assumed to be equal to the incoming liquid temperature.

$$T(x, y, t)|_{t=0} = T_{cast} \quad (4)$$

where T_{cast} is casting temperature, K, which is measured in tundish.

2.2.2. Boundary conditions

In the mold, an average heat flux as a function of the casting time is utilized and the boundary heat flux is described by Savage and Pritchard (1954):

$$Q = A - B\sqrt{\frac{z}{V_{cast}}} \quad (5)$$

where Q represents the mold heat flux, W/m^2; A and B are the coefficients relative to heat flux in the mold; z is the distance from meniscus, m; V_{cast} is casting speed, m/min.

In secondary cooling zone, the heat transfer coefficient between the spraying water and slab surface can be calculated through the formula (6) presented by Nozaki et al. (1978):

$$h_{spray} = \frac{1570.0w^{0.55}[1.0 - 0.0075(T_{spray} - 273.15)]}{\alpha} \quad (6)$$

where w represents spray cooling water flux, L/(m^2 s); T_{spray} represents the temperature of the spray cooling water, K; α is a machine dependent calibration factor; h_{spray} represents the spray cooling heat transfer coefficient, W/(m^2 K).

A Newtonian heat-transfer coefficient is then used to compute radiation heat transfer between the slab and surrounding environment as described by Hardin et al. (2003):

$$h_{rad} = \varepsilon\sigma(T_{surface}^2 + T_{ambient}^2)(T_{surface} + T_{ambient}) \quad (7)$$

where ε is the emissivity of slab surface; σ is the Stefan–Boltzman constant, 5.6684×10^{-8} W/(m^2 K^4); $T_{surface}$ represents the slab surface temperature, K; $T_{ambient}$ represents the ambient temperature, K.

3. Inverse heat transfer problem for secondary cooling process

Heat transfer coefficient is of great importance in heat transfer calculation in secondary cooling process. In the present work, an inverse problem model co-operating the numerical simulation for identifying heat transfer coefficient was built.