International Journal of Thermal Sciences 83 (2014) 80–88

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Fuzzy estimation for heat flux distribution at the slab continuous casting mold surface

Hong Chen [a,b], Litao Su [a], Guangjun Wang [a,b,*], Shibin Wan [a], Lihui Zhang [a], Zhaoming Luo [a]

[a] *School of Power Engineering, Chongqing University, Chongqing 400044, PR China*
[b] *Key Laboratory of Low-grade Energy Utilization Technologies and Systems, Chongqing University, Ministry of Education, Chongqing 400044, PR China*

ARTICLE INFO

Article history:
Received 8 November 2013
Received in revised form
16 February 2014
Accepted 19 April 2014
Available online 24 May 2014

Keywords:
Slab continuous casting mold
Heat flux distribution
Inverse heat conduction problem
Fuzzy inference

ABSTRACT

A fuzzy inference method for estimating the heat flux distribution at the metal-mold interface in slab continuous casting is established in this paper. The finite element method is applied to solve the direct heat conduction problem. A set of decentralized fuzzy inference units are established, and the deviations between the calculated and measured temperatures acquired with the thermocouples buried in the mold are taken as the input parameters of fuzzy inference units, and the corresponding inference components are obtained by fuzzy inference. Then the inference components are weighted and synthesized by a weighted integrated approach based on normal distribution function to gain the compensations of the guessed heat flux distribution. Finally, a decentralized fuzzy inference (NDFI) method based on normal distribution weighted approach is formed. Some numerical experiments are performed to study the effects of the number of temperature sensors, different initial guesses of heat flux distribution and measurement errors on the reversion results. Comparisons with both the existing decentralized fuzzy inference (DFI) method and the conjugate gradient method (CGM) are also conducted, and they all show the validity of the inversion method established in this paper.

1. Introduction

Continuous casting is a technology widely used in the metallurgical industry, which has the benefits of saving cost, improving the quality of ingot, using the automatic control technology easily and so on. The mold is the core part of continuous casting system. It would affect the steel solidification process and the surface quality of slab, and further determine the production efficiency of continuous casting machine.

With the rapid development of numerical calculating theory and computer technology, numerical simulation method has been widely applied to study the continuous casting solidification process [1–7]. To obtain the reliable numerical results, it is prerequisite to accurately determine the heat transfer conditions at the metal-mold interface [8–11]. However, the thermal boundary conditions at the metal-mold interface are extremely complicated in practical casting processes, taking into account of the effects of contact stress, surface oxide, roughness, material quality and air gap and so on [12–16].

Taking advantage of the temperature measuring information obtained by the thermocouples buried in the mold, the thermal boundary conditions can be predicted with the inverse heat conduction. This method can help to reduce the high cost of experiments and arouses the wide attention of scholars from various countries [16–24]. Guo et al. [16] utilized the sequential function specification method (SFSM) to estimate the metal–die interface heat transfer coefficient in the high-pressure die-casting process. Prasanna Kumar et al. [17–19] applied SFSM to retrieve the heat flux distribution at the metal-mold interface in bar and plate aluminum alloy castings. E. Majchrzak et al. [20] utilized SFSM to identify the boundary heat flux on the continuous casting surface. Huang et al. [21] developed the inverse methodology based on the conjugate gradient method (CGM) for estimating the variation of air-gap resistance at the metal-mold interface. The results show that CGM requires much less computation time, is less sensitive to the measurement errors and needs no prior information, while compared to the least square method. Ranjbar et al. [22] conducted the optimization of experimental design in order to estimate the interface heat transfer coefficient by using CGM during the process

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[*] Corresponding author. School of Power Engineering, Chongqing University, Chongqing 400044, PR China. Tel.: +86 23 65103512.

E-mail address: wangguangjun@cqu.edu.cn (G. Wang).

http://dx.doi.org/10.1016/j.ijthermalsci.2014.04.012
1290-0729/

of Sn–10%Pb solidification. Loulou et al. [23] combined both experimental and numerical procedures solved by using CGM to obtain the thermal contact resistance during the first stage of metal casting. Nowak et al. [24] conducted an effective 3D inverse procedure to retrieve the cooling condition of aluminum alloy in continuous casting process.

Ill-posedness is the basic characteristic of IHCP. Wang et al. [25–27] has developed a decentralized fuzzy inference (DFI) algorithm for the IHCP, which estimates the thermal boundary conditions by weighting and synthesizing the fuzzy inference components. Compared to other common inverse algorithms, such as CGM and Levenberg–Marquardt method (L–MM), this method has obvious better anti-ill-posed. It can effectively reduce the influence of the number of temperature measuring points and measurement errors on inversion results, thus provides a new promising solution for IHCP.

This paper attempts to solve the IHCP of the slab mold by using DFI method, and further improves the weighted integrated approach of fuzzy inference component in the DFI method according to the heat transfer characteristics of the slab mold. A decentralized fuzzy inference (NDFI) method based on normal distribution weighted approach is established for estimating the heat flux at the metal-mold interface in slab continuous casting in this paper.

The finite element analysis (FEA) method is applied to solve the direct heat conduction problem of the slab mold in this paper. A set of one-dimensional fuzzy inference units are constructed. The fuzzy inference component of each fuzzy inference unit which corresponds to the temperature sensor is obtained by using fuzzy inference and utilizing the difference between calculated and measured temperatures acquired with the thermocouples inside the slab mold. And then according to the important degree of the measured information, the fuzzy inference components are weighted and synthesized based on the way of the qualitative analysis and normal distribution respectively, to yield the adjustment values to the initial guesses of the heat flux distribution. Finally, the heat flux distribution at the metal-mold interface in slab continuous casting is accomplished.

In this paper, numerical tests have been carried out to consider the effects of the temperature measuring point configuration, the initial guesses of heat flux distribution and measurement errors on the inversion results. The results obtained by the NDFI are also compared with the results of DFI and CGM. The results show that the NDFI method established in this paper can effectively estimate the heat flux distribution at metal-mold interface with high accuracy and good anti-ill-posedness.

2. Mathematical model of the slab mold

The structure of the slab continuous casting mold is shown in Fig. 1.

The calculation region is only the wide side mold in this paper. And its lengths in x direction and y direction are 1580 mm and 40 mm, respectively. 10 groups of cooling sinks are outside the wide side mold, the distance between the groups is 25 mm, the distance of sinks in the 1st and 10th groups which are at the two ends of the mold is 12.17 mm and the distance of sinks in the other 8 groups is 11 mm. The width of the tank is 6 mm. Temperature sensors are set between cooling sink groups. The distance of temperature sensors is 150 mm and the buried depth y_m is 18 mm.

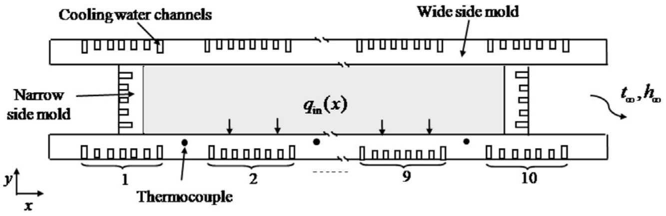

Fig. 1. Schematic diagram of slab continuous casting mold.

The following assumptions are made to concern the characteristics of heat transfer in the slab continuous casting mold:

(1) There is a force convection heat transfer on the outer surface of the mold, which may lead to large temperature gradient along the x and y directions. Compared with the x and y directions, the temperature gradient along the drawing direction is small and could be negligible. Thus, two-dimension heat conduction problem is developed [28,29].
(2) As the casting speed is constant and the change of measured temperatures in a certain period of time is usually small, the heat transfer in the mold is regarded as a steady state.
(3) The physical properties of mold are little affected by temperature, which can be deemed as constants.
(4) The temperature of cooling water is equal at a height of the mold.
(5) The surfaces which contact the narrow side mold are considered to be adiabatic.

The temperature distribution $t(x,y)$ of the slab mold can be obtained by the following equation:

$$\frac{\partial^2 t(x,y)}{\partial x^2}+\frac{\partial^2 t(x,y)}{\partial y^2}=0 \quad 0\le x\le x_1, 0\le y\le y_1 \tag{1}$$

where x_1 and y_1 are the width and thickness of the slab mold respectively.

The thermal boundary conditions are given as:

(1) The heat flux distribution which contacts the slab meets:

$$-\lambda_{cu}\frac{\partial t(x,y)}{\partial y}=q_{in}(x) \quad y=y_1 \tag{2}$$

where λ_{cu} is the thermal conductivity of the slab mold.

(2) The surfaces which contact the cooling water meet:

$$-\lambda_{cu}\frac{\partial t(x,y)}{\partial n}=h_w[t(x,y)-t_w] \tag{3}$$

where n is the direction normal to the contact surface, t_w is the temperature of cooling water, is the heat transfer coefficient of cooling water, determined from the following dimensionless correlation [29]:

$$\frac{h_w D}{\lambda_w}=0.023\left(\frac{u_w\rho_w D}{\mu_w}\right)^{0.8}\left(\frac{c_w\mu_w}{\lambda_w}\right)^{0.4} \tag{4}$$

where D is the hydraulic diameter, u_w is the velocity of cooling water, ρ_w is the density of cooling water, μ_w is the viscosity of cooling water, λ_w is the thermal conductivity of cooling water and c_w is the specific heat capacity of cooling water.