International Journal of Heat and Mass Transfer 111 (2017) 1087–1097

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Estimation of heat transfer coefficients in continuous casting under large disturbance by Gaussian kernel particle swarm optimization method

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ARTICLE INFO

Article history:
Received 28 October 2016
Received in revised form 20 January 2017
Accepted 29 March 2017

Keywords:
Heat transfer coefficients
Inverse heat conduction problem
Gaussian kernel
Particle swarm optimization
Continuous casting

ABSTRACT

The work presented in this paper focuses on the estimation of the heat transfer coefficients by measured surface temperatures which contains large disturbances. In previous works on the calculation of heat transfer coefficients from the measured surface temperatures, the impact of large disturbance on the accuracy of the estimation of heat transfer coefficient was not considered. To solve this problem, we introduce an integrated approach which contains Gaussian Kernel (GK) function and the Particle Swarm Optimization (PSO) algorithm. Moreover, we use the real industrial data of the SAE 1800 slab from Baosteel Corporation to show the validity of this new approach. The simulation experiment results show that our GK-PSO method can reduce the influence of large disturbances effectively. Finally, we use the corrected heat transfer coefficients to improve the accuracy of the heat transfer model. The model can be used to predict the shell thickness of slabs, the predicted results are also validated by the actual measured data.

1. Introduction

Continuous casting is an important solidification process of the molten steel. Fig. 1 is the schematic representation of the continuous casting process showing the process clearly. Molten steel is poured from tundish into a mold which is primary cooling zone. Initial solidification happens in mold after which the solidifying steel enters the secondary spray cooling zone. Continuous casting is also a continuous heat extraction process which can be described by the heat transfer model.

Various related works have studied it and many continuous-casting models have been given. According to the application in practice, these models can be classified into two categories. The first kind of model is used in the model-based online control systems and it satisfies the requirement of real-time [1–6]. They are not sophisticated, but effective enough. The second belongs to the offline model aiming to improve the strand quality [8,26,27]. They are very sophisticated and complex, but they are not feasible when applied in a real-time operating environment. The heat transfer model proposed in this paper belongs to first kind model.

The heat transfer model plays a vital role in continuous casting, so the boundary conditions should be corrected. The reason why we correct the boundary conditions is that the heat transfer coefficient which is the most important parameter of the boundary conditions cannot be measured directly [7]. We can solve the inverse heat conduction problem (IHCP) to correct the heat transfer coefficients by using some actual measured surface temperatures of steel slabs. Many researchers have been studying this problem. By using the surface measured temperatures, Santou et al. [12] estimated the heat transfer coefficients in 2006. In 2007, a new method which combined Newton method and hybrid genetic algorithm, developed by Kim and Baek [15], was used to reconstruct the boundary conditions of a two-dimensional concentric cylindrical medium. In 2009, Slota [11] presented the genetic algorithm (GA) to calculate the heat transfer coefficients. The artificial bee colony algorithm was used successfully to solve a one-dimensional inverse continuous casting problem [13]. In 2012, the heat flux was reconstructed based on the measured surface temperatures by the Homotopy perturbation method [14]. In 2014, a new method combining conjugate gradient method and the method of genetic algorithm was developed by Baghban et al. [16] to reconstruct the boundary conditions.

By using some measured surface temperatures, we can correct the heat transfer coefficients. However, due to the bad environment condition of production in continuous casting, the measured surface temperatures are often noisy and uncertain. These uncertainty and noisy data can be defined as outliers. In statistics, an outlier is an observation point that is distant from other observations. An outlier may come from variability in the measurement

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.03.105
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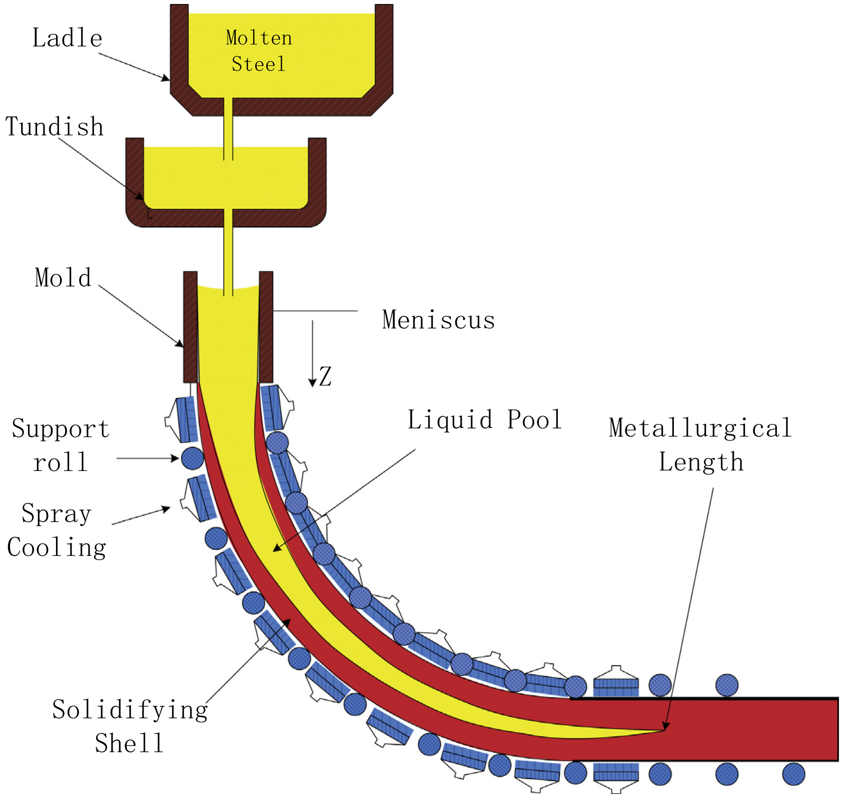

Fig. 1. Schematic representation of the continuous casting process.

or it may indicate infrequent experimental error, which occurs infrequently [17,18]. There are mainly two kinds of method applied to deal with outliers. The first method is called data processing by deleting the outliers directly before using these measured data [19]. To use this method, we first need to rely on the priori knowledge to distinguish the outliers. However, the priori knowledge is often difficult to obtain. The other method is robust modelling and it can deal with the outliers effectively without relying on the prior knowledge [20].

As shown in Fig. 2, the occuring of oxide skin of steel slabs is hard to avoid in the continuous casting. It is the oxide skin of steel slabs that causes the outliers in our measured surface temperatures. That is to say, when the position chosen to measure the surface temperature of the slab has oxide skin, the outlier will exist in our measured temperature data. There is little study on the "outlier" problem in continuous casting, especially on the methods to solve IHCP. Obviously, those outliers influence our estimation accuracy of the heat transfer coefficients. Thus, it is meaningful and practical to develop a method to deal with outliers.

The GK-PSO method proposed in this paper can deal with the outliers automatically and effectively without relying on the prior knowledge. First, we see the IHCP as an optimization problem whose cost function was expressed by the sum of squares of residuals (difference between measured temperature and simulated temperature). However, this cost function is sensitive to the outliers, which influences the accuracy of the heat transfer coefficients. In this paper, we rewrite our cost function of the IHCP, which reduces the effect of the outliers effectively. Then, we use the particle swarm optimization (PSO) algorithm to solve this new cost function to obtain the heat transfer coefficients.

The structure of the rest of the paper is as follows. In Section 2, the heat transfer model used in this paper is introduced. In Section 3, a new cost function which can reduce the influence of the outliers effectively is described. Then, the process of GK-PSO method is introduced to obtain the heat transfer coefficients. In Section 4, we introduce the simulation experiment which uses the measured data with outliers to estimate the heat transfer coefficients shows that our integrated method can reduce the influence of the outliers effectively.

2. Mathematical model

2.1. Heat transfer model

The heat transfer model used here is the first kind of model introduced in Section 1 (Introduction).

Since the requirement of the real-time, we simplify the model by posing some reasonable assumptions in continuous casting [6,19–23]. (1) The surface of meniscus is regarded as flat. (2) The changes of geometry size of casting slab caused by the thermal expansion and contraction can be ignored. (3) The temperature drop of molten steel from tundish to the meniscus area of the mold can be ignored. (4) The density of water flow in the same cooling section of the secondary cooling zone is evenly distributed on the surface of the slab. (5) Convective heat transfer can be equivalent to the thermal conduction in continuous casting. (6) The latent heat during solidification in continuous casting can be regarded as an equivalent specific heat. (7) The heat conduction along the casting direction (z direction) can be ignored.

Figs. 1 and 3 show the continuous casting process clearly. According to the assumption (6), this process can be described as the following simplified heat transport equations [11].

$$\rho(T)C_p(T)V_{cast}\frac{\partial T}{\partial z} = k(T)\frac{\partial^2 T}{\partial x^2} \tag{1}$$

We know that the following equation holds:

$$V_{cast}\partial t = \partial z \tag{2}$$