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A hybrid soft sensor for measuring hot-rolled strip temperature in the laminar cooling process

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ABSTRACT

To overcome the difficulties associated with the frequently varying operating conditions of the laminar cooling process and measuring the strip temperature in the cooling process online, a soft sensor model of the hot-rolled strip is proposed which combines mathematical and hybrid intelligent methods. The proposed approach is based on computational intelligence techniques, where RBF neural networks, CBR and fuzzy logic reasoning are employed to estimate process parameters for predicting the coiling temperature of the strips. A number of simulation tests using industrial data are conducted where the desired numerical results are obtained. It has been shown that the proposed soft sensor has a high potential for being used to effectively measure the strip temperature in the laminar cooling process.

1. Introduction

The laminar cooling system is used to cool the strips from the austenitic finishing temperature (820–900 °C) down to the ferrite coiling temperature (500–700 °C) which can improve the metallurgical properties of the hot rolled strip [1,2]. Strips enter the laminar cooling zone after the finishing mill, they are then cooled in the water cooling section, and finally they are coiled by coilers. The strips' mechanical properties are determined by the strip temperature which is controlled in the laminar cooling zone. Therefore, effective control of the cooling system is extremely important for strip quality. However, the temperature of the water vapor in the cooling process is generally very high, so it is difficult to measure the strip temperature continuously in the cooling zone. Indeed, only the strip surface temperature before it enters the cooling zone can be measured, but the strip temperature cannot be obtained due to a lack of suitable instruments. Only when the strip has been coiled by the coilers can the strip coiling temperature be measured, by which time the cooling operation is complete. So, the closed loop control cannot be effectively conducted. For this reason, a soft sensor is needed to measure the strip temperature in the cooling zone which will be a basis of implementing effective closed-loop control.

Earlier work on modeling the laminar cooling process goes to mathematical equations [3,4]. In order to enlarge the scope of strip specifications, Xie et al. [5] and Chai and Wang [6] developed an error compensation model based on neural networks to improve the precision of the prediction model. However, these models are static and cannot be used to predict the temperature dynamically for the hot rolling strip in the laminar cooling process. In [7], a mathematical model was proposed by using the heat transfer mechanism and a differential equation. The output of the equation actually gives an average temperature along the strip thickness. For thick strips, the temperature difference in the thickness direction cannot be ignored [8]. To reduce the model bias caused by the temperature difference in the thickness direction, Uetz et al. [9] assumed that the temperature density function follows the parabola distribution in the strip thickness direction and established a one-dimensional differential equation system for problem solving. Indeed, some researchers have taken the temperature difference along with time and the thickness direction into account and established two-dimensional dynamic strip temperature models [10–13]. However, the two-dimensional dynamic models cannot be solved effectively and it is hard to apply them for process industries.

The heat transfer mechanism of hot rolling strips in the laminar cooling process is complex, and the heat exchange process parameters are difficult to be estimated by simple regression models. Most of heat exchange process parameters are provided by domain workers based on their working experience. In [6], the strips were classified into several categories according to the product specifications, and the corresponding heat transfer coefficient, heat conductivity coefficient and temperature conductivity coefficient for each category were set accordingly. As we know that the heat transfer process is associated with many factors including the strip specification, cooling water temperature, the environment temperature, and the strip running speed. These factors are varying in the laminar cooing process, and make the improvement on the strip temperature

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model to be limited. Over the past years, many efforts have been made on the model improvement through advanced parameter identification techniques along with the changing boundary conditions. In the petrochemical industry, a cost function for the parameter identification is defined as deviation between the model output and actual output, and the traditional least squares techniques have been employed for the parameter optimization [14,15]. Although quadratic (nonlinear) programming techniques and genetic algorithms can be used for the unknown parameter estimation of dynamic models in the laminar cooling process, online solutions cannot be achieved due to the real-time constraint.

This paper is built on our previous work on modeling the laminar cooling process [16,17], where a two-dimensional parameterized model, the case-based reasoning (CBR) and GA-based optimization techniques have been used. In [16], we considered the influence of changing conditions on the model parameters, but did not address how to set up the initial case base of the case-based reasoning system. Also, the retrieval weight, an important parameter in the case-based reasoning system, was determined subjectively. In [17], a hybrid parameter identification method was proposed to deal with uncertainties caused by the strip specification.

This paper aims to improve the soft sensor model performance in terms of the prediction accuracy of the strip temperature in the cooling process. A mathematical model is firstly developed for predicting the strip temperature, followed by a dynamical tuning of the model's parameters according to varying operating conditions. In this work, RBF neural networks are employed to adjust the weight parameter of the CBR system to improve the system performance. Simulations were carried out on real data from an industrial process. Results indicate that the proposed soft sensor model has good potential to favorably estimate hot strip temperature in the cooling process.

2. Laminar cooling process

The general layout of the laminar cooling process is shown in Fig. 1 with top headers and bottom water sprays. During this process, first the strip will be sent into the run-out table (ROT) after being exported from the finishing mill, then it will be water-cooling in a long cooling zone and finally rolled by the coilers. The cooling water is pumped into the two main water pipes from the water head tank and then distributed by the water dividing pipes. The motors mounted under the ROT are used to control the rolling speed of the ROT. The main function of the laminar cooling system is to regulate the quantity of the cooling water in order to control the coiling temperature of the strip.

In the cooling zone, it is difficult to measure the strip temperature because of two factors: one is that the strip steel produces a lot of high temperature gas during the cooling process. In this situation, it is unavailable for instruments to measure the strip temperature accurately. The other one is that the strip moves quickly in the cooling zone, making the instruments unable to sample accurately in a short time. Therefore, there are only two temperature measuring points mounted at the entry and exit of the cooling zone. In the cooling process, the open loop control cannot guarantee the coiling temperature to meet the technological requirements which are related to product quality. However, in the absence of continuously measured data of the strip temperature, it is difficult to implement conventional closed loop control because the controlled cooling process has already finished before the coiling temperature is sampled. Therefore, in order to implement a real-time control in the cooling process, it is vital to design an online soft sensor model to estimate the values of the strip temperature.

3. Mathematical model of strip temperature

In order to reduce the negative effect on the strip temperature model caused by strip thickness and speed, we define a strip segment with one meter length. At the same time, the strip thickness is divided into several layers. In addition, a pair of vertically symmetrical spray header is defined as a cooling unit. Only three kinds of cooling ways can work in the defined cooling unit, described as follows: (1) If the pair of spray headers are all open, the strips are cooled by water both on the top and bottom surface; (2) If the top spray header is open and bottom header is closed, the strips are cooled by water on the top of the strip surface and cooled by air on the bottom; (3) If the pair of spray headers are all closed, the strip is cooled by air on both the top and bottom of strip surface. These variants imply a need to establish three kinds of heat exchanging models according to the three cooling ways.

As shown in Fig. 2, a small section of the strip in the cooling zone is selected at time τ, where x is the strip direction, y denotes the direction of the thickness, and z denotes the transverse direction. For the non-homogeneous temperature distribution inside the selected strip section, a small element is defined as its volume given by $(dx\ dy\ dz)$. During the unit time, the quantity of the heat entering this element is defined by R_{in}, whilst the heat out of this element is denoted by R_{out}. The heat produced inside this element is denoted by R_g and the energy variation is given by R_{st}. Ignoring the thermal distortion and expansion, by using the law of conservation of energy and the Fourier theory, the heat exchanging model can be described in (1) as follows:

$$R_{in} - R_{out} + R_g = R_{st} \tag{1}$$

According to physics, the generalized heat transfer equation of the selected element can be established as follows:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+\dot{Q}=\rho c_p\frac{\partial T}{\partial \tau} \tag{2}$$

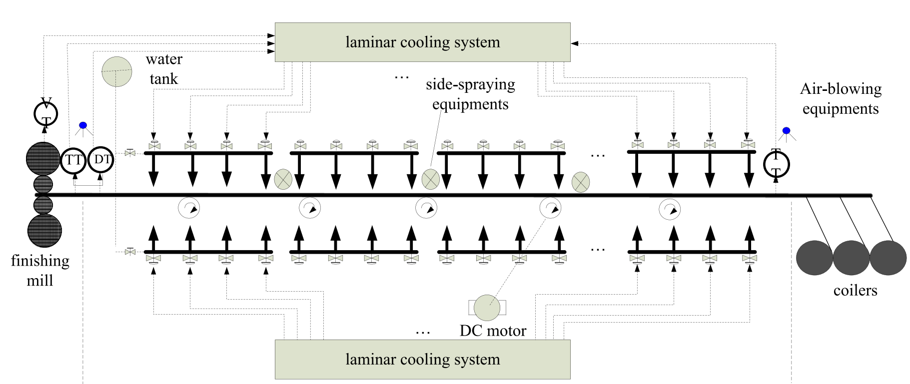

Fig. 1. The general layout of the laminar cooling process.

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