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On-line Ladle Lining Temperature Estimation by Using Bounded Jacobian Nonlinear Observer

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Abstract: The knowledge of transient temperature of the ladle wall is a key factor in optimizing energy consumption in steelmaking process. The transient temperature needs to be estimated. A nonlinear lumped parameter model was used to model the thermal dynamics of the ladle. Then, the bounded Jacobian nonlinear observer was utilized to estimate the temperature. With this method, the estimation model became a closed-loop model and the observer gains were obtained by solving linear matrix inequalities and simply implemented to the system. Comparison between the simulation and recorded data at a participating steel plant in Thailand showed that the nonlinear observer accurately estimated the temperature of the ladle lining. This estimated temperature was very useful in determining suitable tapping temperature for energy conservation and steel quality.

Key words: observer design; nonlinear observer; ladle lining; temperature estimation; Jacobian nonlinear observer; thermal model

In a steelmaking process, the temperatures of the ladle and molten steel before tapping are important for controlling the quality of the product and optimizing the energy consumption[1-5]. Based on the cycle of the steelmaking process, there are two critical processes before the tapping process[4]. One is the preheating and heating of the ladle (stations 1 and 3) and the other is the melting of the metal scrap (station 4). Thus, refractory materials of ladles have been studied and developed to reduce the heat loss during the processes[2,5].

Ladle lining temperature can be used to estimate the energy of a ladle, the heat loss from the ladle, and the thermal expansion stress[6]. Moreover, the ladle lining temperature can be used to optimize the temperature of molten steel in electric arc furnace (EAF). This can help minimize tapping temperature and ensure molten steel temperature at the appropriate values at casting station. As a result, the steel quality can be controlled.

To control the temperatures, the temperature of the molten steel can be measured and estimated inside the EAF. However, the transient temperature of the ladle lining is difficult to measure. Thus, researchers have tried to develop methods to estimate the temperature of the ladle lining and the steelmaking process[3,4,7-11].

In previous work, many ladle models based on thermodynamics and conservation of energy were presented[12,13]. These methods were useful for simple thermal analysis, but difficult to apply in practice due to the harsh operating environment and unknown parameters of the steelmaking process. Meanwhile, two-dimensional dynamic models of ladle were developed. These models needed to be solved by complicated numerical methods or a commercial software package such as COMSOL Multiphysics[3,11]. Neural networks were applied to construct models to predict the temperature[14]. Besides, the models were based on extreme learning machine and AdaBoost. RT were also developed[15,16]. As well, a grey-box approach was used and the root mean square error was applied to calibrate parameters of the model[9]. In these cases, a lot of parameters needed to be measured and complicated algorithms were needed. Fredman, Olena, and Samuels-

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son et al.[7-9] took the advantages of keeping the thermal field computations at a relatively simple level. The model was based on the assumption that the outer lining layers were in a quasi-steady-state, while the working layer was in a transient state. Then, the one-dimensional linear temperature model was solved for the temperatures.

There were models and methods developed to estimate the ladle temperatures. However, most of them were open-loop system/models whose accuracies depended on the complexity of models, initial conditions, and boundary conditions.

Recently, Rumpairujipong et al.[17] developed multiple one-dimensional linear lumped capacitance models for applying linear observer to estimate the temperatures. This method took the advantage of a closed-loop system/model by using the measurement to correct the transient temperature of the ladle lining. The results obtained by this method seemed reliable. However, due to the non-linearity of the system, six linearized models were used and six linear observers were designed. Gain scheduling was then used to switch between these observers. Thus, it was not convenient to implement these observers to the system. Besides, it seemed that there was no guarantee to the stability of the system during switching the models.

Therefore, the one-dimensional nonlinear models and nonlinear observer design were utilized to develop a simple closed-looped observer to estimate the transient temperature of the ladle lining in this paper. With this method, there was no need of multiple linear models. The stability of the system could be guaranteed and it was simple to implement.

1 Dynamic Model of Ladle

Fig. 1 shows the cycle of the steelmaking process[4]. The assumptions for the ladle model are as follows:

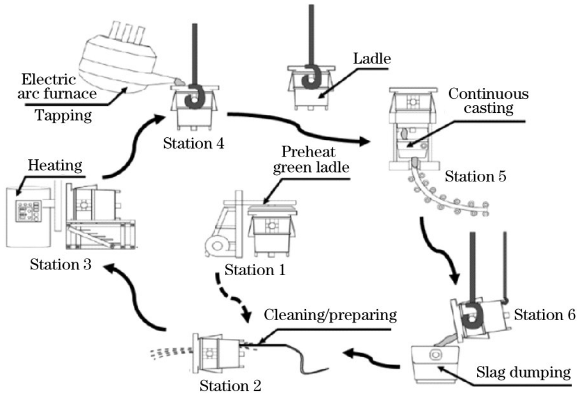

Fig. 1 Cycle of steelmaking process

(1) The ladle wall is cylindrical. The slope of the wall is very small.

(2) The radius of the ladle is large. The heat transfer analysis is considered only along the r-axis as shown in Fig. 2.

(3) There is no heat resistance between layers of the ladle.

Then, the one-dimension ladle model is presented in Fig. 2.

The heat conduction for a finite region is shown in Eq. (1).

$$\rho c\,\frac{\partial T(r,t)}{\partial t}=k\,\frac{\partial^2 T(r,t)}{\partial r^2} \tag{1}$$

where, ρ is the wall density for each layer; c is the specific heat of the wall; T is the temperature; r is the wall thickness; k is the thermal conductivity; and t is the time.

During preheating the ladle at stations 1 and 3, there is heat transfer from fuel, which is defined by

$$F\sigma(T_{\mathrm{fl}}^4-T^4(r,t))=-k\,\frac{\mathrm{d}T(r,t)}{\mathrm{d}r} \tag{2}$$

where, F is the view factor; σ is the Stefan Boltzmann constant, 5.67×10^{-8} W/(m^2 · K^4); and T_{fl} is the flue gas temperature. T_{fl} is controlled by a re-

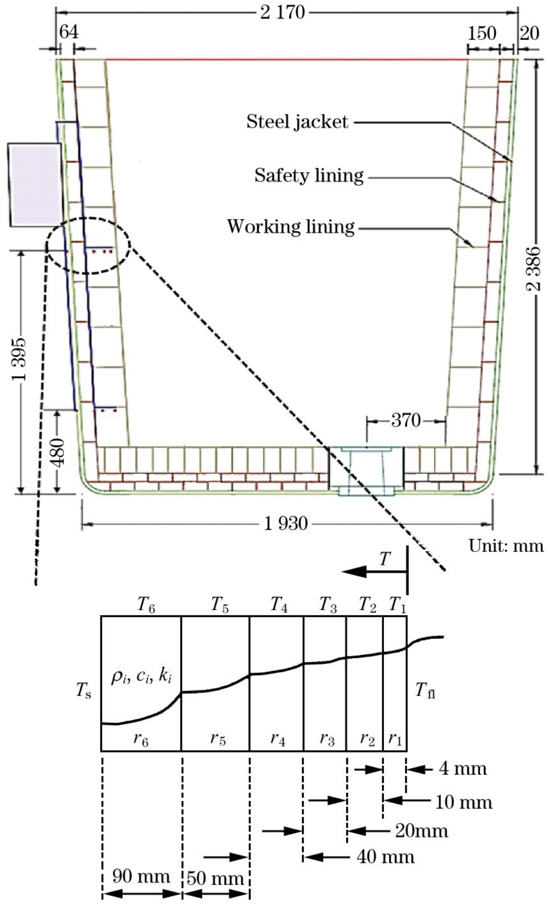

Fig. 2 Schematic representation of ladle wall model