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Multiple time steps optimization for real-time heat transfer model of continuous casting billets

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ABSTRACT

In this paper, the real-time problem of heat transfer model for continuous casting billets has been converted to an optimization problem of multiple time steps. In the optimization problem, the time steps as the optimal variables were constrained by the numerical stability. Furthermore, the objective function was defined by the relative calculation time, and the calculations were subject to the accuracy constraint determined by the maximum absolute temperature difference from the reference grid system. The optimization problem has been solved by particle swarm optimization (PSO) algorithm, by introducing a penalty factor for the accuracy constraint. Results and corresponding analysis show that when the penalty factor is big enough, especially when it tends to positive infinity, the optimized time steps are only determined by the accuracy constraint, independent of the penalty factor and also computers.

1. Introduction

In the model-based online control systems [1–6] for continuous casting billets, real-time heat transfer model plays an important role as the kernel that provides the feedback data. In such case, the real-time of model is of central importance for it is the precondition for online application. The real-time requirements include both efficiency and accuracy, that is to say, the model must be fast enough and be sufficiently accurate.

However, it is difficult to fulfill both of the two requirements synchronously during numerical calculation. The main reason is that the large calculation amount exceeds the capability of present industrial computers. The large calculation amount arises from numerically solving the heat transfer model, which is in form of partial differential equation with initial and boundary conditions. In the solving process, using coarse grid division and large time step can greatly reduce the calculation amount, but this will also reduce the accuracy.

Up to now, most of the real-time heat transfer models for continuous casting process are developed for slabs. These models are either one-dimensional [1,6–8] in each transverse cross section (so-called slice) or two-dimensional [3,9,10] in the longitudinal cross section. They are cost effective for real-time calculations. However, the same model is not valid for continuous casting billets, because the heat transport of billets in each slice is essentially at least two-dimensional. Due to the limit of efficiency and accuracy, most of the heat transfer models for billets are developed just for caster designing or operating parameters optimizing and can only simulate casting conditions offline [11–14]. Real-time heat transfer models for billets can rarely be found in the literatures.

In this paper, a real-time algorithm by optimizing the time steps has been presented for two-dimensional heat transfer model of continuous casting billets, which is based on our previous work [15], where multiple non-uniform grid divisions and multiple time steps have been adopted according to the temperature distribution and the model has been solved by finite volume method (FVM) and alternative direction implicit (ADI) algorithm. In this paper, by applying the previous algorithm, the real-time problem of model about efficiency and accuracy can be generally converted to an optimization problem of multiple time steps to achieve the extreme real-time performance. In the optimization problem, the multiple time steps as the optimal variables are constrained by the numerical stability, the objective function is defined by the relative calculation time, and the calculations are subject to the accuracy constraint. The optimization problem has been solved by particle swarm optimization (PSO) algorithm by introducing a penalty factor for combining the accuracy constraint to the single objective function.

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Finally, results and analysis show that, when the penalty is big enough, especially when it tends to positive infinity, the optimized time steps are only determined by the accuracy constraint and are independent of the penalty factor and also computers. The minimum relative calculation time indicates the extreme real-time performance of target computer.

2. Real-time heat transfer model of continuous casting billets

The heat transfer process of continuous casting billets can be generally described by the heat transport equation. And in considering the following assumptions: (1) increasing heat conduction induced by the flow of non-solid steel can be take into account by an increased effective thermal conductivity; (2) the latent heat released during phase transformations can be considered in the equivalent specific heat; (3) heat conduction in the casting direction can be ignored as it is quite small compared to the transverse cross-directions. The equation takes the following form in the follow-up coordinate system:

$$\rho c_{eff}\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(k_{eff}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{eff}\frac{\partial T}{\partial y}\right) \tag{1}$$

where T is the temperature; ρ is the density of steel; $c_{eff} = \mathrm{d}H/\mathrm{d}T$, H is the enthalpy; $k_{eff} = f_s k_s + m(1-f_s)k_l$, f_s is the solid fraction and k_s, k_l are separately the thermal conductivity of solid phase and liquid phase. The thermal properties including ρ, H, f_s, k_s and k_l are assumed to be functions of T and of the steel compositions and can be calculated by a special algorithm based on pseudobinary phase diagram [16].

In the model, the strand is considered as a queue of two-dimensional slices with fixed distance between two neighbor ones. Each slice starts from the meniscus, moves on and terminates at the straightening point. Considering the symmetry, only one quarter of each slice is selected to be the calculation domain. Initial condition of each slice is assumed equal to the casting temperature:

$$T(x,y,0)=T_c \tag{2}$$

Boundary conditions are specified as follows:

(1) in the mold [17]:

$$-k\frac{\partial T}{\partial n}=A-B\sqrt{t} \tag{3}$$

where t is the experienced time of slice in the mold from the meniscus.

(2) in the secondary cooling zones (SCZ), heat exchange with water and thermal radiation has been considered:

$$-k\frac{\partial T}{\partial n}=h_i(T-T_w)+\varepsilon\sigma\left(T^4-T_a^4\right) \tag{4}$$

where h_i is the heat transfer coefficient of section i in SCZ, ε is the emissivity of billet surface, σ is the Stefan–Boltzmann constant, T_w is the water temperature and T_a is the air temperature.

There can be two kinds of sections in SCZ, one is equipped with water sprays and the other is equipped with air-mist sprays. For water spray cooling:

$$h_i=\frac{1570w_i^{0.55}[1-0.0075(T_w-273)]}{\alpha_i} \tag{5}$$

For air-mist spray cooling:

$$h_i=\frac{1000w_i}{\alpha_i} \tag{6}$$

where w_i is the water flow density(L/m^2/s) of section i, α_i's are machine-dependent parameters.

(3) in the air cooling zone (ACZ), thermal radiation is considered:

$$-k\frac{\partial T}{\partial n}=\varepsilon\sigma\left(T^4-T_a^4\right) \tag{7}$$

Eqs. (1)–(5) define the heat transfer model. The model's numerical solution is available by finite volume method (FVM) [2] and alternative direction implicit (ADI) algorithm. Here, FVM–ADI algorithm is cost effective for FVM is more efficient than finite element method and ADI algorithm is more efficient than explicit algorithm with the same accuracy constraint [15]. In the FVM–ADI algorithm, the heat transfer model is discretized to a set of difference equations by integration of the finite volume of each node in the slice from t to $t + \Delta t$:

$$\int_s^n\int_w^e\int_t^{t+\Delta t}\rho c_{eff}\frac{\partial T}{\partial t}dtdxdy=\int_t^{t+\Delta t}\int_s^n \times\int_w^e\left[\frac{\partial}{\partial x}\left(k_{eff}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{eff}\frac{\partial T}{\partial y}\right)\right]dxdydt \tag{8}$$

where w, e, s, n are the interfaces of neighbor volumes and Δt is the time step.

For online application, the real-time requirements of heat transfer model include both efficiency and accuracy. The efficiency depends on the number of nodes in the strand, time steps and computer's operational speed:

$$t_{cal}=t_p\sum_{i=1}^{n_z}\left(n_x n_y\frac{t_s}{\Delta t_i}\right) \tag{9}$$

where t_{cal} is the calculation time, t_p is the average time cost of each difference equation, n_x, n_y are separately the number of nodes along x direction and y direction, t_s is the control/sample period and Δt_i is the time step of slice i. n_z is the number of slices in the strand:

$$n_z=L/d,\, d\le v_{cast}\cdot t_s \tag{10}$$

where L is the calculation length along the strand, d is the slice distance and v_{cast} is the main casting speed of strand.

Eq. (9) indicates that the calculation time is mainly determined by the grid divisions and time steps of slices in the strand. Fine grid divisions will cause a disaster of huge calculation amount and cannot fulfill the efficiency requirement; instead, using coarse grid divisions can reduce the calculation amount but also cause a lack of accuracy. To balance the efficiency and accuracy, we developed a real-time algorithm based on multiple non-uniform grid divisions and multiple time steps according to the temperature distribution of slice in the strand [15], as shown in Fig. 1. In the real-time algorithm, the whole calculation length is divided into several calculation zones. Each of the calculation zones uses a set of different grid division and time step. When a slice is traveling from zone to zone along the casting direction, the grid divisions and time steps become coarser and coarser as the maximum temperature gradients in the slice are tending to deduce. When grid divisions change, the nodes in the coarser grid division inherit the temperature values directly from last grid division. This is called an inheritable grid system. Furthermore, in a certain calculation zone, the grid division of slice is non-uniform: the grids become coarser and coarser from the boundary to the center, according to the temperature distribution.

3. Stability analysis

In order to find the upper limit of Δt, stability analysis of inner nodes in the slice is conducted by using von Neumann method