Development and Application of Dynamic Soft-reduction Control Model to Slab Continuous Casting Process

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Based on the heat transfer and solidification model for simulating two-phase zones by coupling multiple alloys during slab continuous casting process and the soft-reduction theory, the dynamic control model for soft-reduction on slab continuous casting was developed. The control model consists of three major functional modules: real-time tracking simulation, cooling water control and dynamic soft-reduction control. In order to keep stable continuous casting and produce high quality slabs during slab continuous casting process, many significant operating parameters such as the cooling water at the secondary cooling zone and the roll gap at sector section can be dynamically adjusted according to the reasonable metallurgical criterion and on-line feedback information. Industrially, the model has been successfully applied. Industrial practices indicate that the control model with reasonable algorithms and accurate simulation has a certain theoretical value and industrial practicality.

KEY WORDS: slab continuous casting; dynamic soft reduction; dynamic control at the second cooling zone; control model.

1. Introduction

During slab continuous casting process, casting speed and temperature of the molten steel usually vary with the change of slab casting process. For example, casting speed will decline due to the mold breakout prediction system alarms or the SEN changing; molten steel temperature in each ladle on turntable is also different.1,2) The solidification of molten steel, with non-steady-state characteristics, can be on-line controlled and monitored through real-time forecasting and feedback controlling by computer simulation model.3–8) The factory operators are able to acquaint clearly themselves with the real slab state of heat and stress through the forecast and the control of solidification heat transfer. Thus the operators can adjust the operating parameters to make the process of continuous casting more flexible under the limitation of metallurgical criteria.9–11)

As one of the effective methods to reduce the center segregation in slabs, dynamic soft-reduction technology11–18) needs to accurately predict the non-steady final solidification point and the solidification state of the slab. It is the most dominant factor for dynamic soft reduction. Due to the unfavorable circumstances in the closed room of the secondary cooling zone, the present thermometric technology is hard to factually report the on-line slab temperature and the position of the solidification end point. In addition, detecting element is far from the demand of the feedback control. Therefore, up to now the computer control model based on numerical simulation prediction is generally one of the popular methods to achieve dynamic soft-reduction control. This paper describes a dynamic soft reduction model and its algorithm characteristics, and introduces the practical application of the soft reduction to the improvement of slab quality.

2. Algorithm Description

The dynamic soft-reduction control model mainly consists of three theoretical algorithm modules, including the algorithm of real-time tracking simulation, the algorithm of dynamic cold water controlling, and the algorithm of dynamic soft-reduction controlling.

2.1. Real-time Tracking Simulation Algorithm

The heat transfer and solidification model is the key theory of slab continuous casting metallurgical process.19,20) Based on the theory of heat transfer and solidification, dynamic control model can be used to track and control the fluctuation of operating parameters promptly, and the industrial process can effectively benefit from this model. With thorough understanding on the solidification and transport theory, the slab heat transfer and solidification model is also gradually perfected. Influencing factors are more comprehensively considered, and heat transfer boundary conditions at the mold and at the second cooling zone are more precise. The characteristics of the model are listed as follow:

- Convection influence coefficient is used to describe the impact effect of liquid steel flows on the effective thermal conductivity, which can be approximately processed according to the overheating value, casting distance and
solid fraction.\textsuperscript{21,22)}

- Thermo-physical properties of steels like specific heat, thermal conductivity and density are calculated by considering different phase constitution, such as liquid phase, $\delta$ and $\gamma$ phase. The effective thermal conductivity is determined by the arithmetic mean value of the series connected and parallel type thermal conductivity.\textsuperscript{23)}

- The non-equilibrium solidification routes are determined by the analytic solidification equation which is iteratively calculated and deduced from the micro-segregation model of solidification in two-phase zone in multiple alloys.\textsuperscript{23)}

- The release of latent heat during the solidification process is considered based on the specific heat conversion. In other words, effective specific heat is used for the specific heat of steel at mushy zone.\textsuperscript{24)}

- A variety of factors like usage and temperature rise of cooling water, casting speed, slab width, slab length, and the location of mold are comprehensively considered to determine the local heat flux in the mold.\textsuperscript{24,25)}

- At the secondary cooling zone, the slab heat loss affected by heat dissipation mechanisms is described by an integrated heat transfer coefficient. According to the calculation by static simulation model under the boundary conditions of heat transfer in reality, the integrated heat transfer coefficient at the secondary cooling zone is determined.\textsuperscript{24,25)}

The algorithm of real-time tracking simulation is based on the concept of limited laminated layer. The vertical center section of the slab is taken for study and separated into several thin laminated layers (slicing units), which move down along the casting direction with the casting speed. The computational domain of model is numerically discretized, as shown in Fig. 1. The slicing units start at the meniscus and end at the out gate of caster. The total residence time of the slicing unit is defined as a life-cycle of the continuous casting machine. The life cycle of each slicing unit dominated by the casting speed is the same in the continuous casting machine. The life cycle of each slicing unit is defined according to its current location. Combining with tracking cycle of the current slicing unit, the corresponding temperature information is reflected on the corresponding slicing unit in concrete cooling region.

Due to the complex physical phenomena during continuous casting process and the requirements of real-time computing, it is difficult to model all of the factors. The following assumptions are used in the current model:

1) The heat transfer in the casting direction ($Z$) and the slab width direction ($\chi$) is ignored; only the heat transfer in the slab thickness direction ($Y$) is considered.

2) Molten steel is incompressible Newtonian fluid, the thermal physical properties of steel are considered as constant.

3) The release of latent heat during solidification is considered based on heat conversion method. Namely, effective specific heat ($c_{eff}$) is used in two-phase mushy zone instead of the specific heat ($c_p$):

\begin{equation}
    c_{eff} = c_p - \Delta H_f \frac{\partial f_s}{\partial T}
\end{equation}

where $c_{eff}$ is the effective specific heat in J/(kg·°C); $c_p$ is the specific heat in J/(kg·°C); and $f_s$ is the solid fraction.

4) The convective thermal conductivity of molten steel is considered as effective thermal conductivity:

\begin{equation}
    \lambda_{eff} = n\lambda
\end{equation}

where $\lambda_{eff}$ is the effective thermal conductivity in W/(m·°C); $\lambda$ is the thermal conductivity in W/(m·°C); and $n$ is the correction factor ($n=5$–$10$). In the mushy zone, the effective thermal conductivity can be calculated by:

\begin{equation}
    \lambda_{eff} = \lambda f_s + n\lambda(1 - f_s)
\end{equation}

where $f_s$ is the solid fraction. The solid fraction can be calculated by:

\begin{equation}
    f_s = \frac{T_L - T}{T_L - T_s}
\end{equation}

where $T$ is the local temperature in °C, $T_L$ is the liquidus temperature in °C; and $T_s$ is the solidus temperature in °C.

With the assumptions, the slab temperature field can be described by the following partial differential equations:

\begin{equation}
    \rho \cdot c_{eff} \frac{\partial T}{\partial t} = \frac{\partial}{\partial y} \left( \lambda_{eff} \frac{\partial T}{\partial y} \right)
\end{equation}

where $\rho$ is the density of steel in kg/m$^3$.

Each slicing unit is completely tracked as it moves during continuous casting process. The heat transfer boundary condition of each slicing unit is determined by the casting distance. In each tracking cycle, the new slicing unit generated at the meniscus is endowed with the real-time pouring temperature. Other real-time information like the current casting speed, the flow rate of cooling water on each mold surface, the water temperature rise between outlet and inlet on each mold surface, the water flow rate of each control loop, and the cooling water temperature at the secondary cooling zone are also synchronously reported. Casting speed is reflected in all the sections of existing units. Other information is reflected on the corresponding slicing unit in concrete cooling region.

In each tracking cycle, the heat transfer condition of slicing unit is defined according to its current location. Combining with tracking cycle of the current slicing unit, the discrete grid nodes are processed through differential numerical calculation of heat transfer based on the previous corresponding temperature field. Thus the temperature field of the corresponding slicing nodes and the location of solidus–liquidus interface (solidifying front) are obtained. According to the temperature at both upper and lower edges of the slicing nodes, and the distribution of solidified shell thickness, the surface/internal centre temperature of slab and the variation law of solidified shell thickness along the casting direction are reported.

2.2. Algorithm of Cooling Water Control

For slab continuous casting, two popular methods are currently used to control the cooling water. They are water control law\textsuperscript{26)} and dynamic control law.\textsuperscript{27)} The advantages and disadvantages of the two methods are listed in Table 1.

Table 1: Comparison of Water Control Methods

For the dynamic control algorithms of secondary cooling water, effective casting speed is introduced to investigate
the effect of casting history during slab cooling process. Considering the current actual casting speed, the effective casting speed is defined based on the quantity of slicing units and the average casting speed at the secondary cooling zone. The definition can fully reflect the casting history (calculated from the beginning of the slicing unit) of each slicing unit and its effect on the total heat transfer of the caster at the secondary cooling zone. The schematic of method for calculating the effective casting speed is shown in Fig. 2. In the current calculation cycle, the secondary cooling zone totally contains N slicing units (corresponding serial numbers are \( j, j+1 \cdots j+N-2 \) and \( j+N-1 \)). The slicing unit generates at the meniscus and moves toward the out gate of the caster with certain casting speed.

The average casting speed of slice unit \( j \) in m/s can be represented by:

\[
V_{c,j} = \frac{(L + dZm)}{(t + \Delta t)} \tag{6}
\]

where \( L \) is the casting distance from meniscus in m; \( t \) and \((t+\Delta t)\) are the last and the current calculation period respectively in second; \( dZm \) is the moving distance of slice unit \( j \) during the current calculation period \( \Delta t \) in m, which is calculated by:

\[
dZm = V_c \cdot \Delta t \tag{7}
\]

Where \( V_c \) is the actual casting speed in m/s.

The average casting speed of all the slice units at the secondary cooling zone \( i \) can be obtained by Eq. (6). And then the average casting speed of the secondary cooling zone \( i \) can be calculated by:

\[
V_{\Sigma,i} = \frac{(V_{c,1} + V_{c,1+j} + \cdots + V_{c,j+N-2} + V_{c,j+N-1})}{N} \tag{8}
\]

where \( V_{\Sigma,i} \) is the total average casting speed of the secondary cooling zone in m/s; \( N \) is the number of the slice units.

A reasonable fractional factor is necessarily introduced to describe the relationship between the collectivity average casting speed, which can be calculated from the average casting speed contained in each unit in all sections, and the current actual speed:

\[
V_{\text{eff},i} = V_{\Sigma,i} \times C_{\text{frac}}(i) + V_i \times (1 - C_{\text{frac}}(i)) \tag{9}
\]

where \( V_{\text{eff},i} \) is the effective casting speed of secondary cooling zone \( i \) in m/s; \( C_{\text{frac}}(i) \) is the fractional factor of secondary cooling zone \( i \), and \( V_i \) is the actual casting speed in m/s.

Taking into account of the remarkable differences of the distance from the meniscus to the individual secondary cooling partition, and the time that the slicing units with new operating conditions need to move to the individual secondary cooling partition, the value of cooling fractional factor must aclimatize to this technical character. For example, the front parts of secondary cooling zone are closer to the meniscus than other parts, the actual casting speed has more effects on the effective casting speed, and thus the value of fractional factor should be smaller. Contrarily, for the secondary cooling partition which have relatively longer distances to the meniscus, the actual casting speed contribute less to the effective casting speed, the value of corresponding fractional factor should be an appropriate larger number.

Besides considering the history of casting speed, the concept of comparing the target surface temperature to modify the flow rate of cooling water is introduced in the control algorithms. In other words, it is to compare and analyze the theoretical prediction with the target value at the control point along the casting direction. Based on PID algorithm rules, the correction value is calculated according to the deviation. Correspondingly, the flow rate of cooling water at the secondary cooling zone should be regulated to the calculated correction value. The predicted temperature is ensured to accord with the target temperature on the slab surface in some extent. The surface temperature feedback control with casting temperature feed forward was applied in the cooling water control system. The control diagram is shown in Fig. 3. The adjustment of the cooling water at the secondary cooling zone can be represented by:

\[
\Delta Q_i = a_i \cdot f(T - T_{\text{aim},i}) \tag{10}
\]

Where \( T_i \) is the Calculated temperature in °C; \( T_{\text{aim},i} \) is the
target surface temperature in °C; \(a_i\) is the adjustment factor; \(\Delta Q_i\) is the adjustment of cooling water flow rate in L/min; \(i\) is the sequence number of the cooling zone; \(f\) is a function between the water flow rate and the surface temperature.

The proper cooling curves for all the steels should be taken into account as the value of target temperature on the slab surface are defined. The temperature gradient on the slab surface changes suitably along rolling direction at the secondary cooling zone. In addition, as the simulation results indicate, the locations of solidification ends of slabs in different thickness are remarkably different even if with the same surface temperature distribution. The thicker slab has further solidification end. From the aspect of stable heat transfer, the slab thickness should be considered specifically when determining the target surface temperature.

### 2.3. Algorithm of Dynamic Soft-reduction Control

By arranging the reasonable reduction value of sector section roll gap in the solidification ends region, the soft-reduction technology can farthest restrain the flow of thickening liquid in interdendritic of mushy zone, and make a certain reduction to compensate the solidification shrinkage and thermal shrinkage of slab. Thus the purpose of improving the slab quality and avoiding some defects like central segregation and central porosity is achieved.

In each control cycle, the simulation results from the real-time model are used to determine the current internal center temperature and the distribution of solid fraction along the roll direction, which is also called tracking the solidification ends. Afterwards, based on the relevant rules of the control model of soft-reduction (the relative position of reduction starting point and reduction ending point in sector section), the proper soft-reduction zone (soft-reduction in sector section) is given according to the calculation of internal center temperature and solidification. The reasonable soft-reduction fraction and reduction amount depend on the steel grade, the superheat and the mechanism conditions of the caster. Usually the reduction rate is in the range of 0.7–1.2 mm/m. Combining the reduction rate and the working region; the total reduction amount can be obtained. The theoretical value of maximum reduction amount versus steel grade in the current study is listed in Table 2. The actual limit value of roll gaps of the caster is needed to be considered to get the reasonable reduction amount. After giving out the working region and reduction amount, the control model could present the corresponding theoretical value of roll gap according to the initial value of

– However, it must be updated in the next calculation cycle. This approach can avoid the frequent adjustment of the roll gap in sector section of caster, which benefits to the caster condition and slab quality.

Necessarily, three important parameters of soft reduction, such as the soft-reduction zone, the reduction rate and reduction amount, the value of roll gap in sector section, are comprehensively taken into account in the algorithm of dynamic control of soft reduction. The soft-reduction zone primarily depends on the distribution of solid fraction in slab centre. The optimized locations of corresponding starting point and end point are closely related to steel grade. Generally speaking, the starting position of the soft reduction region is usually at the location with 0.3–0.6 in \(f_s\); and the end position of the soft reduction region is usually the location with of 0.8–0.95 in \(f_s\). With the casting speed of 1.1 m/min and the pouring temperature of 1545°C, the predicted temperature distribution and solidification of slab Q345 with soft reduction are shown in Fig. 4. As analyzed by the control model, the reduction zones are segment 7 and segment 8 at the operating condition.

The reduction rate in working region mainly depends on the steel grade, the superheat, the roll distance, and the mechanism conditions of the caster. Usually the reduction rate is in the range of 0.7–1.2 mm/m. Combining the reduction rate and the working region; the total reduction amount can be obtained. The theoretical value of maximum reduction amount versus steel grade in the current study is listed in Table 2. The actual limit value of roll gaps of the caster is needed to be considered to get the reasonable reduction amount. After giving out the working region and reduction amount, the control model could present the corresponding theoretical value of roll gap according to the initial value of

![Fig. 3. The schematic diagram of cooling water control.](image-url)

![Fig. 4. The temperature distribution and solidification of the slab.](image-url)
roll gap for individual sector section.

In order to make the function of the soft-reduction effectively and protect the sector section frame, two significant functions, the sequential control at sector section and the adaptive adjustment of reduction amount, are introduced to the dynamic control algorithm of soft reduction. The sequential control means that, at the beginning of the soft reduction, the model tracks the reduction position and applies the reduction real time. But the roll gaps of the segments after the reduction area are not applied until the slab at the reduction position has already passed the segment. The adaptive adjustment of reduction amount means that, if the actual soft reduction force exceeds the limit of soft reduction force which depends on the segment framework, the reduction amount will be gradually reduced appropriate value to protect the segment framework.

3. Development of Model

Based on the above theoretical algorithm, a control model of dynamic soft-reduction was developed in the current study, which includes three modules: real-time tracking simulation module, cooling water control module and dynamic soft-reduction control module, as shown in Fig. 5.

The real-time tracking simulation module was developed from the mathematical model of heat transfer and solidification. Compared with the offline static simulation model, the biggest difference is that the real-time tracking simulation module could memorize the cooling history during slab continuous casting process and on-line predict the real continuous casting process of slab, which has the characteristic of real-time calculation. Due to the restriction of tracking cycle, the real-time tracking model should be necessarily simplified for some purposes. Therefore, besides considering some metallurgical factors like heat transfer boundary conditions and solidification characteristics of steel in two-phase region, the discretization of calculation region should also be taken into account.

![Fig. 5. The module map of the control model of dynamic soft-reduction.](image)

Based on the predicted results (the central temperature on the inner radius surface) from real-time tracking simulation module, the cooling water control module could dynamically adjust the flow rate of secondary cooling water according to the specific control algorithm (in view of the cooling history of slab and the target surface temperature curve). The model interfaces are shown in Fig. 6.

![Fig. 6. The user interface of secondary cooling.](image)

The control module of dynamic soft reduction adjusts the segment gap dynamically based on the slab temperature and solid fraction. The correct implementation of soft-reduction technology mainly depends on the rationality of the real-time tracking simulation module, as shown in Fig. 7.

![Fig. 7. The block diagram of the control model of dynamic soft-reduction.](image)

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### Table 2. The theoretical value of maximum reduction amount versus steel grade.

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Ultra-low carbon steel</th>
<th>Low carbon steel</th>
<th>Peritectic steel</th>
<th>Medium carbon steel</th>
<th>High carbon steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum reduction amount (mm)</td>
<td>3.0</td>
<td>3.5</td>
<td>3.8</td>
<td>4.0</td>
<td>4.5</td>
</tr>
</tbody>
</table>
Industrially, corresponding operating software was developed based on the soft reduction control model. The operating software has very good versatility and practicality. Besides several major operation interfaces mentioned above, there are other four interfaces, such as the editing interface of basic data, the editing interface of simulation parameters, the editing interface of steel properties, the viewing interface of caster structure.

- In the editing interface of basic data, some important operating parameters like the schedule of secondary cooling water and the roll gap in sector section could be perfected.
- In the editing interface of simulation parameters, some important simulation parameters like the integrated heat transfer coefficient and target surface temperature could be corrected.
- In the editing interface of steel properties, the steel grade and its thermo-physical properties could be chosen, added, edited and deleted.
- For different slab continuous casting machine, the users can choose the proper information in light of the actual situation.

4. Industrial Practice

Industrially, the real-time tracking and dynamic control model has been successfully tested and applied on No. 6 continuous casting slab machine in Liu steel, in November 2007. The industrial practice conditions are listed in Table 3. Through detailed on-site debugging work, the functions of long-range adjustment of roll gap, the real-time tracking of solidification process, the dynamic control of secondary cooling water, and the static control and dynamic control of soft-reduction could run very well. The corresponding parameters for static and dynamic soft-reduction for hot trial are shown in Fig. 8.

In the industrial practice the slab continuous casting machine ran stably and the casting process was smooth. The slab product in the industrial production indicated that the slab-surface temperature was uniform, roll gap control was precise, the slab was regular, and no abnormality was observed. The macroscopical photos showed that, under the same production condition, the centre segregation of slabs from was remarkably improved after the application of soft reduction, as shown in Fig. 9. As several industrial practices indicated, the centre segregation of slab ameliorated 1.5 levels than former one after the application of soft reduction.

In order to validate the reliability of the simulation results, the slab surface central temperatures were measured in the industrial production. The comparison of results is listed in Table 4.

The above calculation results predicted by the model match the actual measured temperature on the slab surface in industrial production very well. In most cases, the deviation between them is less than 15°C (a few specific points reach 25°C). The deviated average value is ~8.8°C. From the aspect of theory or actual practice, the deviation range is acceptable.

5. Conclusion

Comprehensively, the dynamic soft-reduction control model with powerful function is embedded with three main modules.

(1) In real-time tracking simulation module, the concept of mobile slicing unit is used to track the process of solidification of slab on-line. The space between two adjac-
puter-controlled measure. It can also provide the caster op-
used in the industrial slab continuous casting as a com-
accurate simulation. Thus the model can be successfully
The model has reasonable control algorithms and preferable
paid good agreement with the actual measured temperature.
practices and the measured results indicated that the whole
cess successfully applied in No. 6 slab Caster in Liu steel. Industrial
in the current model. In industry, the model has been suc-
heat transfer of slab during solidification is fully considered
The effect of various operating parameters history on the
puting cycles, accurate heat transfer boundary conditions.
(2) In the dynamic control module of secondary cool-
ing water, the concept of effective casting speed is intro-
duced to investigate the cooling history of the slicing unit.
According to the comparison between theoretically pred-
tected temperature and target temperature at the control
point along the rolling direction, the flow rate of secondary
cooling water is dynamically adjusted.
(3) In the control module of dynamic soft reduction,
soft-reduction zones and soft-reduction sector sections are
determined based on the real-time tracking simulation re-
sults and a certain algorithm laws. Then, according to the
casting steel and casting conditions, the reasonable reduc-
tion fraction and reduction amount are initialized in order
to dynamically adjust the roll gap in sector section.
The current model has a large number of advantages,
such as developed and reasonable algorithms, short com-
puting cycles, accurate heat transfer boundary conditions.
The effect of various operating parameters history on the
heat transfer of slab during solidification is fully considered
in the current model. In industry, the model has been suc-
cessfully applied in No. 6 slab Caster in Liu steel. Industrial
practices and the measured results indicated that the whole
model control process is stable and reliable. And the slab
quality was improved in a certain extent (especially the cen-
tre-segregation). The predicted central surface temperature
paid good agreement with the actual measured temperature.
The model has reasonable control algorithms and preferable
accurate simulation. Thus the model can be successfully
used in the industrial slab continuous casting as a com-
puter-controlled measure. It can also provide the caster op-
erators with more accurate metallurgical real-time informa-
tion through simulation calculation. And it aids in guaran-
teeing good quality and stability of the slab products. It has
significant theoretical value and favorable industrial appli-
cation.

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Table 4. Predicting and measuring temperature of slab sur-
face.

<table>
<thead>
<tr>
<th>NO.</th>
<th>Casting speed m/min</th>
<th>Sector section</th>
<th>Calculated temperature °C</th>
<th>Measured temperature °C</th>
<th>Deviation °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.3</td>
<td>Seg10-11</td>
<td>894</td>
<td>897</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>1.3</td>
<td>Seg13</td>
<td>900</td>
<td>919</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>1.3</td>
<td>Seg10-11</td>
<td>938</td>
<td>945</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>1.2</td>
<td>Seg10-11</td>
<td>944</td>
<td>944</td>
<td>-3</td>
</tr>
<tr>
<td>5</td>
<td>1.1</td>
<td>Seg13</td>
<td>915</td>
<td>929</td>
<td>14</td>
</tr>
<tr>
<td>6</td>
<td>1.15</td>
<td>Seg10-11</td>
<td>933</td>
<td>934</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>1.15</td>
<td>Seg7-8</td>
<td>957</td>
<td>969</td>
<td>12</td>
</tr>
</tbody>
</table>

Fig. 9. Center segregation of slab in macroscopy.