A Practical Model for Predicting Intermixed Zone During Grade Transition

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This article proposes a new mixing model for predicting the composition distribution in continuously cast steel during a grade transition. The transient model consists of two sub-models, one for mixing in the tundish and the other for mixing in the liquid pool of the strand. The Cho and Kim's simple tundish mixing model (which is very efficient and practical) is adopted as the present tundish model. For the mixing model in the strand, the concept of Cho and Kim's tundish model was extended to the strand. In order to verify the proposed model, plant tests were conducted on three kinds of casters (slab, bloom and thin slab caster) during the grade transition period of continuous casting under various conditions. The real grade intermixed slabs and blooms were produced and the composition distributions were measured and compared. When the proposed model was applied to several cases of the slab, bloom and thin slab casting, the numerical results were found to be in good agreement of the experimental data. These findings verify that the proposed model is capable of tracking mixing phenomena for arbitrary casters and operating conditions.

KEY WORDS: grade transition; continuous casting; intermixed zone.

1. Introduction

Sequential casting of different grades of steel is increasingly required to meet the customer's demand for fast delivery of small quantity orders for steel products. Since this successive casting produces undesirable grade-mixed steels which should be cut out as scrap, it is important to know the exact location of the intermixed region. To minimize the length of the undesirable intermixing zone and to optimize the casting conditions, it is necessary to predict the final composition distributions produced within the continuous cast slabs or blooms during the arbitrary grade transition.

The conventional method of predicting the composition in the intermixed region extracts the prediction function on the basis of experiments such as water model or real plant test. Another method is the 3-D transient numerical simulation considering tundish filling and casting speed changes. Although these methods give us precise data on mixing during the grade transition, they require much effort and time. Even when the geometry or operating condition of the caster is changed, these methods still call for as much time and effort as they used to before.

Pioneers in the area of developing an efficient intermixing model to predict the mixed region during a grade transition, Huang and Thomas have developed a model for predicting the intermixed region within several seconds as opposed to the conventional methods that used to take several days or even weeks. Their model is designed to consider the mixing within both the tundish and the strand. It covers any kinds of casters by introducing eight parameters which have to be defined according to the geometry of the tundish and the strand. However, this model also requires a great deal of experimental data to tune its eight parameters.

Recently, Cho and Kim have developed a new tundish mixing model which has only one parameter related with the tundish geometry for convenient replication and efficiency. Since their model has only one parameter, it can be easily tuned after one or two experiments. However, since this model is limited to the tundish mixing, it is not capable of predicting the intermixed zone of the final products to cut out.

This article proposes a new mixing model for covering both the tundish and the strand by extending Cho and Kim's simple tundish mixing model to the strand region.

2. Cho and Kim's Simple Tundish Mixing Model

Cho and Kim have developed a novel tundish mixing model designed to minimize the number of parameters to only one that needs to be tuned for easier application to new situations. Their model was verified through the cases of the two water models and real bloom casting.

In their mixing model, the composition of the liquid is specified as a dimensionless “concentration” $C$:

$$C = \frac{F(t) - F_{\text{old}}}{F_{\text{new}} - F_{\text{old}}}$$

where $F(t)$ is the fraction of a given element in the alloy and $t$ represents time. $F_{\text{old}}$ and $F_{\text{new}}$ are the fraction of that ele-
ment measured in the old and new grades, respectively. They assumed that the concentration leaving the tundish \( C_{TD} \) is related with the average concentration \( C_{avg} \) and the inlet concentration \( C_{in} \) (shown in Fig. 1). The relation between \( C_{avg} \), \( C_{TD} \) and \( C_{in} \) is assumed to be

\[
C_{TD}(t + \Delta t) = f_{TD} \cdot C_{avg}(t + \Delta t) + (1 - f_{TD}) \cdot C_{in}(t + \Delta t) \quad \text{......(2)}
\]

where \( f_{TD} \) is a scale factor to be determined and is related to the tundish shape.

And, \( C_{avg} \) is calculated as

\[
C_{avg}(t + \Delta t) = \frac{M_{in}(t) \cdot C_{in}(t) + Q_{in}(t) \cdot \rho \cdot \Delta t \cdot C_{in}(t)}{M_{TD}(t + \Delta t)}
\]

\[
- \left( \sum_{j=1}^{n} Q_{out}^{j}(t) \cdot \rho \cdot \Delta t \cdot C_{TD}(t) \right) \quad \text{......(3)}
\]

\[
M_{TD}(t + \Delta t) = M_{TD}(t) + \rho \cdot Q_{in}(t) \cdot \Delta t - \left( \sum_{j=1}^{n} Q_{out}^{j}(t) \cdot \rho \cdot \Delta t \right)
\]

\[
\text{where } n \text{ is the number of outlets from the tundish, } \rho \text{ is the density of the molten steel, } M_{TD} \text{ is the weight of molten steel within the tundish and } Q \text{ represents the volume flow rate of molten steel (m}^{3}/\text{s}).
\]

The main steps of Cho and Kim’s tundish mixing model are as follows:

1. Obtain the starting values \( M_{TD}(t) \), \( Q_{in}(t) \), \( Q_{out}(t) \), \( C_{in}(t) \), \( C_{TD}(t) \), \( C_{avg}(t) \) and \( f_{TD}(t) = t_{ref} \) at the first step, \( t = t + \Delta t \).
2. Update the tundish weight \( M_{TD}(t + \Delta t) \) by means of Eq. (4).
3. Calculate the average concentration \( C_{avg}(t + \Delta t) \) in the tundish at \( (t + \Delta t) \) step by employing Eq. (3).
4. Calculate \( C_{TD}(t + \Delta t) \) from Eq. (2).
5. Update the time \( t = t + \Delta t \). Terminate the iteration, if the calculation time is enough. Otherwise continue with step 1.

3. Extending Cho and Kim’s Tundish Model to the Strand

In this article, Cho and Kim’s tundish mixing model is extended to the strand region to predict the intermixed zone of the final product through a grade transition. During the ladle change for grade transition, the casting speed, the flow rate into the tundish, and the molten steel level in the tundish vary with time. Tundish mixing begins when a new ladle is opened, and a new grade of steel starts to flow into the tundish. The behavior of the mixing depends on the shape of the tundish including the shape of the dam and the weir, as shown in Fig. 1, and it also depends on the operating condition such as the time varying inflow \( Q_{in} \), the outflow \( Q_{out} \), and the molten steel level in the tundish. After leaving the tundish, mixing occurs in the strand. Diffusion is negligible in solid shell, including the entire surface of the strand below the meniscus. Turbulent flow within the liquid pool may bring mixed molten steel far below the position of the meniscus. Huang and Thomas\(^{(10,11)} \) have simulated the composition difference between the center and the surface in a section of the mixed zone according to the casting speed. They found that a slower casting speed greatly reduces the extent of mixing in the strand. At the same time the slower speed of the shell also decreases the metallurgical length. These investigations revealed that casting speed during grade transition is greatly decreased to minimize the strand mixing in the real plant operation. And in general, the same formulation occurs across the cross section of the strand used in the real caster.\(^{(1,2)} \)

Based on this background, we assumed that the incoming mixed steel through the tundish outlet is fully mixed in the restricted region \((x = -L, \text{ shown in Fig. 1})\) of the strand and uniformly solidified. Then, the weight \( M_{MD} \) of the mixing region in the strand can be defined as

\[
M_{MD} = \rho \cdot W \cdot H \quad \text{..................(5)}
\]

where \( W \) is the mold width and \( H \) represents mold thickness. We assumed that the concentration leaving the restricted region \((x = -L)\) \( C_{MD} \) is related with the average concentration \( C_{Move} \) in the strand and the incoming concentration \( C_{TD} \) through tundish (shown in Fig. 1). The relation between \( C_{TD} \), \( C_{MD} \) and \( C_{Move} \) is assumed to be

\[
C_{MD}(t + \Delta t) = f_{MD} \cdot C_{Move}(t + \Delta t) + (1 - f_{MD}) \cdot C_{TD}(t + \Delta t) \quad \text{......(6)}
\]

where \( f_{MD} \) is a scale factor to be determined. The \( f_{MD} \) represents the mixing behavior in the strand. The average concentration \( C_{Move} \) in the restricted region of the strand is calculated as

\[
C_{Move}(t + \Delta t) = \frac{M_{MD} \cdot C_{Move}(t) + Q_{out}(t) \cdot \rho \cdot \Delta t \cdot [C_{TD}(t) - C_{MD}(t)]}{M_{MD}}
\]

\[
\text{...................(7)}
\]

The main steps of the present mixing model are sketched in Fig. 2.
4. Verification

To verify the proposed model, an extensive verification and calibration was performed on the tundish and strand mixing models, and it was validated with measurements from several different continuous casting machines, including the slab, bloom and thin slab caster.

A schematic diagram of the first tundish (called boat type) for slab casting is shown in Fig. 3. The tundish has one inlet (from ladle) and two outlets (to strands). The maximum inner volume of this tundish is designed to be 70 tones. The operation conditions for grade transition include refilling the tundish from 10.0 to 60.0 tones in 230 s while the casting speed ramped back up from 0.0 to 1.2 m/min over 300 s. To compare the result of the proposed mixing model with the actual plant product, a grade intermixed slab of 12 m×1.28 m×0.23 m that includes the mixed portion was cut into several slices, and the compositions (C and Mn) were measured at each cross section of the slice.

The concentration contours and profiles of the measured components for carbon and manganese, each converted to dimensionless composition with Eq. (1), are shown in Figs. 4 and 5. These experimental data indicate that the composition difference between the slab surface and the center is not significant. This result reconfirmed that the molten steel near the center can not penetrate deep within the liquid pool since the casting speed during grade transition is greatly decreased. Figure 5 compares model predictions with compo-
sition measurements in the slab. The zero point on the coordinate axis “Distance up slab” represents the position of the meniscus at the time of opening the new ladle. In order to minimize the errors between the experimental data and the present model, the parameters, $f_{TD}$, $f_{MD}$ and $L$ were tuned to the values of 1.18, 1.0 and 0.7 respectively by the genetic algorithm. In Fig. 5, the predictions of concentration change with different sets of model parameters are compared to the experimental data. It is found that the values of parameters were successfully tuned. Figure 5 also shows that the proposed model predicted well that the composition would steeply increase during tundish filling and the gradient of composition increment would decrease after filling.

The calibrated model ($f_{TD} = 1.18$, $f_{MD} = 1$ and $L = 0$) for the slab caster with the boat type tundish was applied to different casting operations. The relevant casting conditions are given in Table 1. The predicted results are compared with the measurement data in Figs. 6 and 7, which show that the proposed model predicts the concentration history in the intermixed zone very well, and that its result is in good agreement with the measurement data. The measurements were based on a chemical analysis of drilling chips taken near the surface and the centerline of the slabs.

In a different case, the bloom caster was investigated to test the proposed mixing model. The tundish (20 tons) of this bloom caster has 1-inlet (ladle) and 4-outlets (strands with 250 mm×330 mm cross section), as shown in Fig. 8. This tundish has already been studied by Cho and Kim in a full scale water model experiment. They found that $f_{TD} = 1.0$ is the proper value for this bloom tundish. The comparison between model predictions ($f_{TD} = 1.0$, $f_{MD} = 1$ and $L = 0.7$) and measurements of bloom composition is given in Figs. 9 and 10. The casting speed was decreased from 1.0 to 0.0 m/min for 300 s, held as a stop for 150 s, and increased up to 1.0 m/min for 300 s. The measurements were conducted along the produced bloom surface and the centerline for manganese and chrome alloy contents. Figures 9 and 10 indicate that excellent agreement was obtained between predictions and measurements. These also show that $f_{MD} = 1$ and $L = 0.7$ (which tuned from the above slab case) were still proper in this bloom case.

For the final verification, a thin slab caster with two ladles and one strand was considered as shown in Fig. 11. Two ladles provide the molten steel to the tundish of 50 tons in sequence. The molten steel of the tundish flows into the thin slab mold with a 100 mm×1200 mm cross section. During the grade transition, the tundish was filled from 22.8 tons to the 50 tons in 305 s at a constant casting speed of 5.0 m/min. As shown in Fig. 12 which compares the model prediction ($f_{TD} = 1.2$, $f_{MD} = 1$ and $L = 0.7$) with the composition measurement in the slab, the computed results of the proposed mixing model were found to

| Table 1. | Casting conditions of slab caster for model validation. |
|-----------|-----------------|-----------------|
| **Input condition** | **Case-I** | **Case-II** |
| Slab thickness | 230mm | 230mm |
| Slab width | 1280mm | 1380mm |
| Number of strands | 2 | 2 |
| Minimum tundish weight at new ladle open | 15.0 tons | 12.0 tons |
| Normal tundish weight | 65 tons | 70 tons |
| Minimum casting speed | 0.0 m/min | 0.0 m/min |
| Steady casting speed | 1.5 m/min | 1.5 m/min |
| Time at minimum speed | 30 s | 30 s |
| Time to ramp speed back | 300 s | 300 s |

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agree fairly well with the experimental data. The value of the tundish mixing related parameter \( f_{TD} \) was changed in comparison with that of the above slab and bloom cases because the different tundish was used, as Cho and Kim\(^{12}\) told. However, the same values as the above slab and bloom cases for the strand mixing related parameters \( f_{MD} \) and \( L \) were also proper in this thin slab case.

Although we could set the strand mixing parameters \( f_{MD} \) and \( L \) to the same values of 1.0 and 0.7 respectively in the above three verification cases, these parameters are related to the mixing in the strand and may be changed according to the condition of the strand mixing. As an example, if the grade separator is inserted through the meniscus to completely prevent mixing and decrease the mixing region in the strand, these two parameters \( f_{MD} \) and \( L \) should be changed.

5. Conclusion

This paper proposed a novel mixing model for predicting the intermixed zone during a grade transition by extending Cho and Kim’s tundish simple model to the strand region. To verify the proposed mixing model, the real grade mixed slabs, blooms and thin slabs were produced through a grade transition continuous casting. When applied to several different continuous casting cases, including slab, bloom and thin slab casting operations, the numerical results of the proposed mixing model agreed well with the experimental data. In the present verification cases, \( f_{MD} \) and \( L \) could be fixed as constant values whereas the constant parameter \( f_{TD} \) was found to be determined according to the tundish shape. However, for the strand mixing related parameters \( f_{MD} \) and \( L \), much further application work is needed.

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