Simple Tundish Mixing Model of Continuous Casting during a Grade Transition

Myung Jong CHO and In Cheol KIM

Technical Research Lab, POSCO, 1, Goedong-dong, Nam-gu, Pohang City, 790-785, Korea.

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A novel tundish mixing model is proposed to predict the outlet concentration of the tundish during a grade transition. To enhance the efficiency and replication performance, the present model was designed to minimize the number of parameters to only one that needs to be tuned for easier application to new situations whereas the Huang and Thomas model has six parameters to be tuned. Two types of water model were employed to verify the present model, and the real grade mixed blooms were produced through a grade transition continuous casting. When the present tundish mixing model was applied to the cases of the water models and real bloom casting, the numerical results of the present model were found to be in good agreement of the experimental data, and the constant parameter *f* of the present model was found to be determined according to the tundish shape.

KEY WORDS: grade transition; continuous casting; tundish mixing.

1. Introduction

To meet the customers' demand for faster delivery of small quantity orders for steel products, the number of castings has been increased with different grades as successive heats in a single casting sequence. Since this successive different grade casting produces undesirable grades of mixed slabs, the steel producers need to know exactly where the mixed region is located that needs to be cut out and to optimize the casting conditions to minimize the costs associated with intermixing different molten steels from different ladles.

Burns *et al.*[1] developed the mathematical formulation of Ashland slab caster to predict the intermixed slab length by using the result of the full scale water model experience. Yeh *et al.*[2] simulated the mixing in the tundish by using a 3-D numerical model based on the k–ε turbulence equation and compared their result with that of the water model experiment. Lan and Khodadadi[3] calculated the mixing in the strand and the slab during steel grade transition, also based on the turbulent 3-D fluid flow and mass transfer. Like these researches, most studies[4–8] related with the grade transition have concentrated on the water model experience or 3-D numerical simulation.

Although these researches gave us information on the mixing during the grade transition, their approaches were extremely time consuming. Even when the geometry or the operating condition of the caster is changed, their methods ask for the same time consumption as before. So, Huang and Thomas[9] developed a very efficient intermixing model to predict the mixed region during a grade transition. With this approach they predicted the intermixed region within several seconds whereas the previous other methods had required several days or weeks. It has eight parameters which have to be defined according to the geometry of the tundish and the strand. In general, two parameters related with the strand out of the eight parameters above can be easily determined from the previous research results[9,10] since the geometry of every strand is very similar to each other. However, the six parameters related with the tundish should be determined on a case by case basis since each tundish has a different dam, weir, and wall shapes. Especially, since most mixing during a grade transition occurs in the tundish, it is important from the viewpoint of calculation accuracy to determine the six parameters related with the tundish geometry, which is not a simple task.

In this article, a simple tundish mixing model is proposed which has the minimum number of one parameter related with the tundish geometry for convenient replication and efficiency (whereas Huang and Thomas model have six parameters).

2. New Tundish Mixing Model

During a ladle change for a grade transition, the casting speed, the flow rate into the tundish, and the molten steel level in the tundish vary with time. 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 and on the operating condition such as the time varying inflow Q_{in}, the outflow Q_{out}, and the molten steel level in the tundish. **Figure 1** shows that the molten steel flow pattern in the tundish (which is strongly related with the mixing behavior) is changed according to the dam and weir.

The composition of the liquid is specified as a dimen-

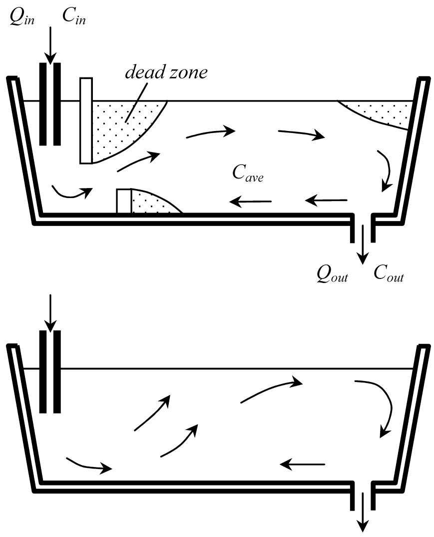


Fig. 1. A schematic diagram of the fluid flow in the tundish.

sionless “concentration” C:

$$C \equiv \frac{F(t)-F_{\rm old}}{F_{\rm new}-F_{\rm old}} \quad \text{.............................(1)}$$

where $F(t)$ is the fraction of a given element in the alloy, and $F_{\rm old}$ and $F_{\rm new}$ are the fraction of that element measured in the old and new grades, respectively. The concentration leaving the tundish $C_{\rm out}$ is related with the average concentration $C_{\rm ave}$ and the inlet concentration $C_{\rm in}$.

In this article, the relation between $C_{\rm in}$, $C_{\rm out}$ and $C_{\rm ave}$ is assumed to be

$$C_{\rm out}(t+\Delta t)=f\cdot C_{\rm ave}(t+\Delta t)+(1-f)\cdot C_{\rm in}(t+\Delta t) \quad \text{......(2)}$$

where f is a scale factor. And, $C_{\rm ave}$ is calculated as

$$C_{\rm ave}(t+\Delta t)=\frac{M_{\rm td}(t)\cdot C_{\rm ave}(t)+Q_{\rm in}(t)\cdot \rho_{\rm in}(t)\cdot \Delta t\cdot C_{\rm in}(t)}{M_{\rm td}(t+\Delta t)} - \frac{\left(\sum_{j=1}^{n} Q_{\rm out}^{j}(t)\right)\cdot \rho_{\rm out}(t)\cdot \Delta t\cdot C_{\rm out}(t)}{M_{\rm td}(t+\Delta t)} \quad \text{..........(3)}$$

$$M_{\rm td}(t+\Delta t)=M_{\rm td}(t)+\rho_{\rm in}(t)\cdot Q_{\rm in}(t)\cdot \Delta t - \left(\sum_{j=1}^{n} Q_{\rm out}^{j}(t)\right)\cdot \rho_{\rm out}(t)\Delta t \quad \text{...............(4)}$$

$$\rho_{\rm out}(t)=C_{\rm out}(t)\cdot \rho_{\rm new}+(1-C_{\rm out}(t))\cdot \rho_{\rm old} \quad \text{............(5)}$$

where n is the number of outlets from the tundish and ρ is the density of the molten steel. Then, the present tundish mixing model has only one parameter (f) that has to be determined by using the water model or real plant experiment data.

The main steps of the present tundish mixing model are summarized as follows:

1. Obtain the starting values $M_{\rm td}(t)$, $Q_{\rm in}(t)$, $Q_{\rm out}^{\rm J}(t)$, $C_{\rm in}(t)$, $C_{\rm out}(t)$, $C_{\rm ave}(t)$ and f ($t=t_{\rm o}$ at the first step).
2. Update the tundish weight $M_{\rm td}(t+\Delta t)$ and density $\rho_{\rm out}(t)$ at the outlet by means of Eqs. (4) and (5).

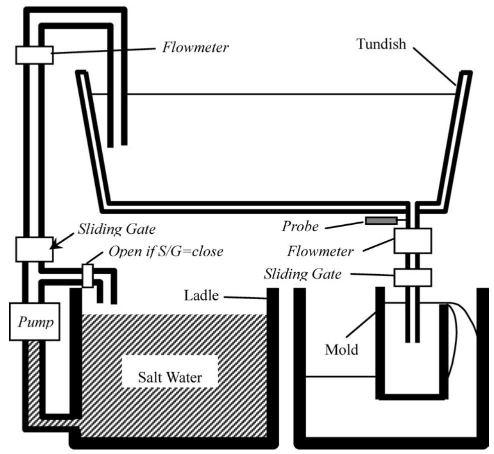
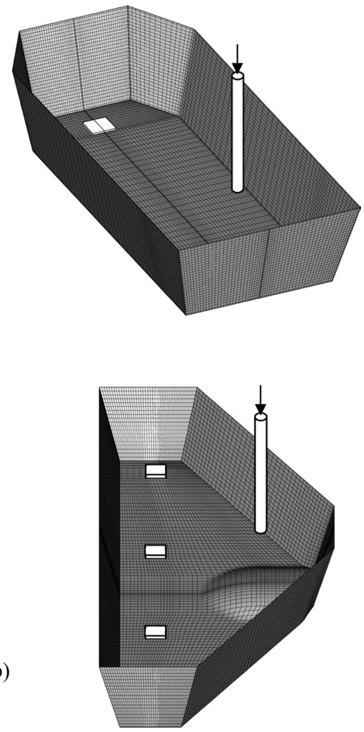


Fig. 2. A schematic illustration of a full scale acrylic-water model.



(a)

(b)

Fig. 3. A schematic view of the tested tundishes. (a) Type-A tundish. (b) Type-B tundish.

3. Calculate the average concentration $C_{\rm ave}(t+\Delta t)$ in the tundish at $(t+\Delta t)$ step by employing Eq. (3).
4. Calculate $C_{\rm out}(t+\Delta t)$ 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. Verification

To verify the present tundish mixing model, the acrylic-water model was employed, and two types of tundish were tested. A schematic diagram of the water model used and the tundish shape are shown in **Figs. 2–4**, respectively. The type-A tundish has one inlet and one outlet, and the type-B tundish has one inlet and four outlets. The maximum volume of both tundishes is designed to be 3.3 $\rm m^3$, which is

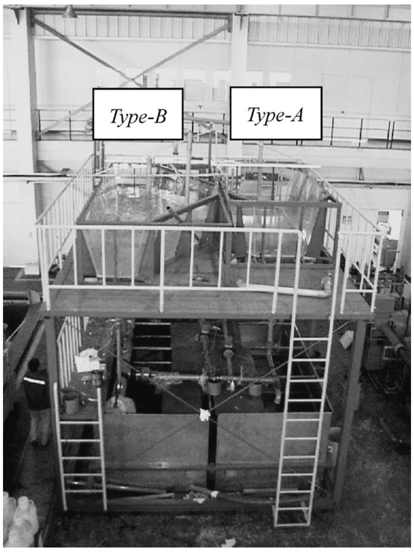


Fig. 4. The used water model.

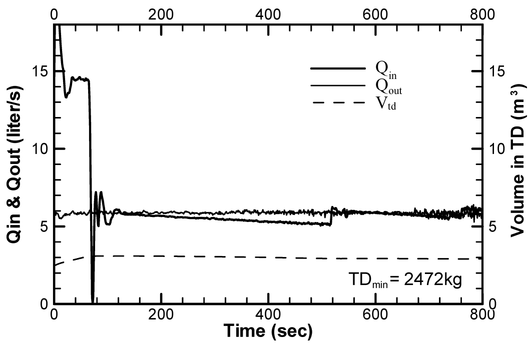


Fig. 5. The measured flow rate and water quantity in the water model tundish (Type-A water model tundish and TD_{min}=2 472 kg).

similar to the total inner volume of a 20 ton tundish in the real plant.

Water was first filled to the full height of the tundish. Water stream was poured from the tundish to the mold by controlling the outlet flow rate. The ladle nozzle was still closed. Therefore, the water level in the tundish descended gradually. When the tundish water level reached the target level, the ladle nozzle was fully opened, and the salt water with a known concentration was continuously injected into the tundish. The concentration at the outlet of the tundish was monitored by an on-line conductivity instrument. At this time, the inlet flow rate was larger than the outlet flow rate, and the water level rose. When the height of the water level reached the operation position, the inlet flow rate was adjusted to be equal to the outlet flow rate.

In **Fig. 5**, the measured flow rate Q_{in}, Q_{out} and the quantity of water in the tundish are described in the case of type-A tundish where the minimum tundish weight TD_{min}= 2 472 kg, which corresponds to 17.8 tons of steel. In order to apply the present mixing model to this case (Type-B, TD_{min}=2 472 kg), the parameter f was determined by the least squares method with the experimental data of the water model after the height of the water level reached the operation position. Three results of the present tundish mixing model with f=1.00, 1.18, and 1.36 are compared with the experimental data for the outlet concentration as shown

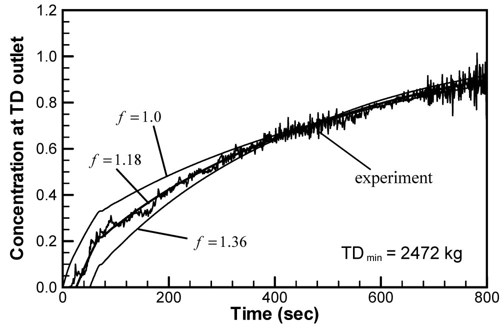


Fig. 6. Effect of the parameter f of the present model (Type-A water model tundish and TD_{min}=2 472 kg).

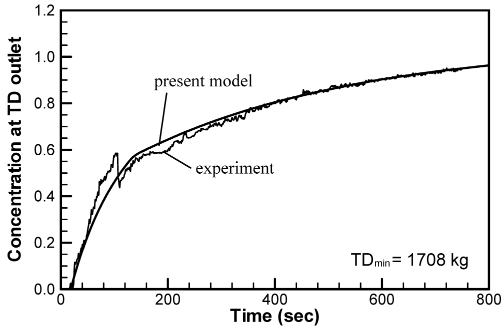


Fig. 7. Comparison of concentration profiles at the tundish outlet (Type-A water model tundish and TD_{min}=1 708 kg).

in **Fig. 6**. This figure shows that f=1.18 is thought to be the optimized value of type-A tundish in the present tundish mixing model. The present tundish mixing model with the optimized scale factor (f=1.18) was applied to the other case (TD_{min}=1 708 kg, corresponding to 12.3 tons of steel) for type-A tundish, and the calculated result is plotted in **Fig. 7**. As shown in this figure, the computed results of the present tundish mixing model were found to agree fairly well with the experimental data. While the water in the tundish is filled up to the normal operation level from TD_{min}, the outlet concentration has steeply increased. After filling, the water level is controlled as a constant. At that time, the gradient of the increment of the outlet concentration is greatly decreased. As a result, the smaller the tundish level TD_{min}, the longer the period during which the outlet concentration is steeply increased. Figures 6 and 7 show that the present model predicts this phenomenon according to TD_{min} very well, and the constant scale factor (f=1.18) is appropriate for the grade transition prediction of type-A tundish.

For a different case, type-B tundish, shown in Fig. 3, was tested. Type-B tundish has 4-outlets whereas type-A has one. **Figure 8** shows the measured flow rate Q_{in}, Q_{out} and the quantity of water in the type-B tundish. The four outlets were controlled to have the same flow rate. In order to check the effect of the outlet position, the concentration was measured at two outlets by considering the symmetry of the tundish shape, which are plotted in **Fig. 9**. This figure shows that the effect of difference of outlet position can be neglected.

The predicted outlet concentration data are also compared with the experimental data in Fig. 9 and **Fig. 10**, which shows that the present tundish mixing model with f=1 predicts the outlet concentration history very well, and

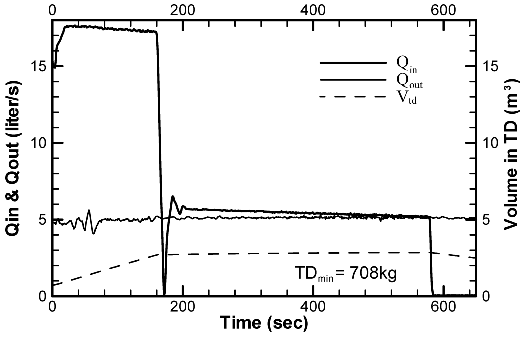


Fig. 8. The measured flow rate and water quantity in the water model tundish (Type-B water model tundish and TD_{min}=708 kg).

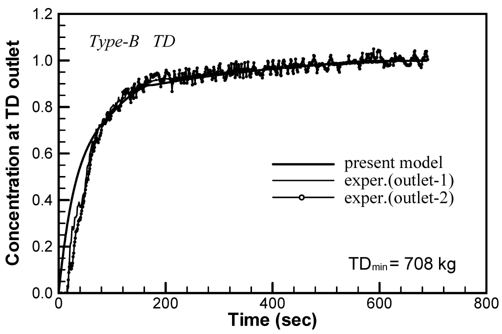


Fig. 9. Comparison of concentration profiles at the tundish outlets (Type-B water model tundish and TD_{min}=708 kg).

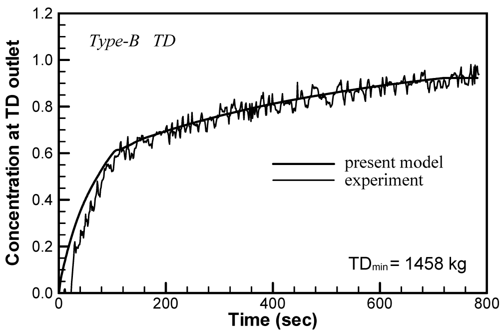


Fig. 10. Comparison of concentration profiles at the tundish outlet (Type-B water model tundish and TD_{min}=1 458 kg).

that its result is in good agreement with the experimental data. For the type-B tundish, f=1.0 seems to be the optimized value.

A second example of the favorable comparison between model predictions (f=1) and measurements of bloom composition is given in **Figs. 11** and **12** for the conditions of a 0.25 m×0.33 m bloom caster with type-B tundish. 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 centerline for manganese and chrome alloy contents, each converted to dimensionless composition with Eq. (1). In the experimental data, the composition at the bloom surface was similar to that at the center. These results show that the most mixing in this case has occurred in the tundish. The present tundish mixing model without considering the mixing in the strand can predict the composition of the final bloom. As the scale factor

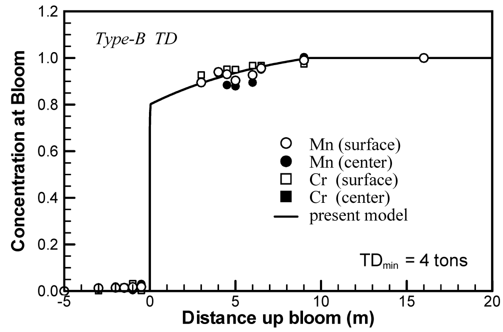


Fig. 11. Comparison of predicted and measured concentration along the intermixed bloom (Type-B real tundish with TD_{min}=4 tons).

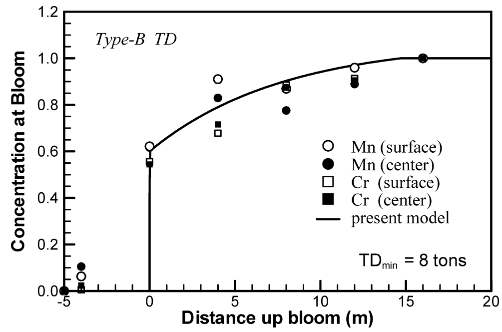


Fig. 12. Comparison of predicted and measured concentration along the intermixed bloom (Type-B real tundish with TD_{min}=8 tons).

of the present model, f=1.0 is used, which was determined from the water model experience. Figures 11 and 12 indicate that a reasonable agreement was obtained between predictions and measurements.

These findings led us to conclude that the present tundish mixing model predicts the outlet concentration in the tundish during the grade transition very well, and that its parameter (f) can be fixed as a constant value, which is determined according to the tundish shape.

4. Conclusion

In this paper, a novel tundish mixing model was proposed to predict the outlet concentration of the tundish during a grade transition. To enhance the efficiency and application performance of the model, the present model was designed to have only one parameter whereas Huang and Thomas model has six parameters to be determined. Two types of water model were employed to verify the present model, and the real grade mixed blooms were produced through a grade transition continuous casting. When the present tundish mixing model was applied to the cases of the water models and real bloom casting, the numerical results of the present model were found to be in good agreement of the experimental data, and the constant parameter f was found to be determined according to the tundish shape.

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