Multiphase Flow Behavior in a Single-Strand Continuous Casting Tundish during Ladle Change

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(Received on August 15, 2019; accepted on September 12, 2019; J-STAGE Advance published date: October 31, 2019)

The three-phase flow behavior in a single-strand continuous casting tundish during ladle change was investigated using physical modeling. These phenomena observed from physical modeling were explained by employing the multiphase model volume of fluid, which can track the interface behavior between the liquid steel, slag, and air during this operation. The effects of the refilling time and lowest operating level on the slag entrainment and the steel exposure during ladle change were analyzed and discussed, respectively. Increasing the refilling time significantly decreased the amount of entrained oil and the exposed area in the impact zone during ladle change. However, the increase in the lowest level had little influence on reducing the slag entrainment. To reduce the slag entrainment and the steel exposure during ladle change, the refilling time in the prototype should be larger than 3 minutes. Furthermore, the use of the turbulence inhibitor has also been evaluated. By diminishing the turbulence intensity in the impact zone and the velocity magnitude at the steel-slag interface, the turbulence inhibitor reduced considerably the amount of entrained slag and the steel reoxidation. The results indicated that the emulsification phenomenon during ladle change could be eliminated using TI-2, and the maximum exposed area fractions in the impact zone for different refilling times and lowest levels were less than 13% and 23%, respectively. Therefore, the TI-2 was recommended to improve the steel cleanliness during ladle change.

KEY WORDS: tundish; ladle change; slag entrainment; slag exposure; physical modeling; numerical simulation

1. Introduction

The continuous casting tundish serves as a buffer and acts as distributors of the liquid steel between the ladle and the mold. Its casting process consists of the steady-state casting and unsteady-state casting. In the past three decades, most of the previous investigations have focused on steady-state casting operations. The flow pattern, heat transfer, and inclusion removal in the tundish could be well optimized by the installation of flow control devices, such as weirs and dams,1–6) baffles with holes,7–9) and turbulence inhibitors.10–13) The steel cleanliness is also strictly controlled.

However, during the unsteady-state casting periods, some adverse phenomena such as the slag entrainment and the steel reoxidation sometimes occur, which have a detrimental effect on the production of clean steel. For example, Tanaka et al.,14) Sahai15) and Deng et al.16) reported that the number of alumina-type and slag-type inclusions in Al-killed steels significantly increased during the casting start and ladle change processes. It could also lead to an increase of the total oxygen in the steel.17,18) Takahashi et al.19) found that the outflow rate of inclusions to the mold increased sharply immediately after the start of pouring from the new ladle. Zhang et al.20) pointed out that the ladle change-over operation induced a high disqualification rate of flaw detection in the steel rails.

Compared with the steady-state operation, it is difficult to study these phenomena in the tundish during the unsteady-state casting. For the casting start or the ladle change, there is a strong entry jet in the tundish inlet. It easily gives rise to the slag and air phases entrained into the liquid steel, thereby forming a complex air-steel-slag multiphase flow. Currently, only a few studies have been reported on the multiphase flow behavior in the tundish during the unsteady-state casting. Garcia-Hernandez and Morales et al.21–23) investigated the phenomena of slag and air entrainment during ladle change-over operations using a conventional ladle shroud (CLS) and the dissipative ladle shroud (DLS). Their results indicated that the amount of air and slag entrained, and the steel reoxidation were considerably decreased when the DLS was adopted. Furthermore, they discussed the effects of three different turbulence inhibitors on the flow pattern in a four-strand tundish during the startup operations of casting sequences.24,25) Zhang et al.20,26) studied the effects of different types of ladle shrouds combined with turbulence

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DOI: https://doi.org/10.2355/isijinternational.ISIJINT-2019-506

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inhibitors on the flow pattern, air and slag behaviors, and steel exposure in a five-strand bloom tundish during both steady-state casting and ladle change-over. They proposed that the optimal combination should be the trumpet ladle shroud and the circular turbulence inhibitor with the eave. Based on the analysis above, the multiphase flow behavior in the tundish during the unsteady-state casting has not been studied in detail.

In the current study, the multiphase flow behavior in a single-strand tundish during ladle change is investigated using physical modeling and numerical simulation. The effects of the refilling time, low limit operating level, and turbulence inhibitor on the slag entrainment and the steel exposure during ladle change are compared and discussed. Furthermore, several effective measures have been also proposed to avoid the slag entrainment and the steel reoxidation in the tundish during ladle change.

2. Experimental Work

2.1. Operating Parameters during Ladle Change

The operating parameters during ladle change were recorded during the production of six heats non-oriented silicon steel. Figure 1 shows the variation of steel weight in the tundish during ladle change. This unsteady-state process can be divided into two stages. One is the drainage process, during which the ladle shroud is closed and the liquid steel level in the tundish decreases to the lowest level. The time interval is defined as the drainage time. The other is the refilling process, during which the liquid steel level in the tundish rises to the normal operating level again. The time interval is defined as the refilling time. The recorded parameters include the steel weights in the tundish at steady state and low limit operating level, the drainage time, and the refilling time. Generally, the normal operating level in the tundish during steady-state casting is about 1100 mm. The lowest level in the tundish during ladle change is approximately 900 mm, corresponding to a steel weight of about 24 tons. However, for Heats 5 and 6, the low limit steel weight in the tundish during ladle change decreases to 21.8 tons. Obviously, the lowest level in the tundish is decreased.

Figure 1 also shows that the ladle change time is different for different heats. When the ladle shroud is closed, the liquid steel level in the tundish gradually decreases. The multiphase flow in the tundish remains relatively stable. The crucial process is the start of pouring from the new ladle. To regain the operating level, the incoming flow rate in the tundish is markedly larger than that at steady state, which generates a strong entry jet dragging slag and air into the liquid steel. The refilling time depends mainly on the incoming flow rate during the refilling process. A shorter refilling time corresponds to a larger incoming flow rate. It may further influence the air-steel-slag flow behavior during ladle change. In this work, the refilling time ranges from 70 to 121 seconds.

2.2. Experimental Procedure

Physical modeling was carried out using a 1/2 scale model of the current tundish. The water represents the liquid steel, and a commercial silicon oil represents the top slag layer. Figure 2 shows a schematic of the experimental setup. The movement of the oil phase was recorded using three CCD cameras during experiments. They are located in front of and above the impact zone, and in front of the outlet zone, respectively. The dimensions and parameters of the prototype and water model are listed in Table 1.

The flow rate and the time interval in the water model are calculated based on the Froude similarity criterion.

![Fig. 2. Experimental setup. (Online version in color.)](image)

### Table 1. Dimensions and parameters of prototype and water model.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Prototype</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating level at steady state (mm)</td>
<td>1 100</td>
<td>550</td>
</tr>
<tr>
<td>Distance between the inlet and the outlet (mm)</td>
<td>3 510</td>
<td>1 755</td>
</tr>
<tr>
<td>Submergence depth of the ladle shroud at steady state (mm)</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>Diameter of the outlet (mm)</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>Inner diameter of the ladle shroud (mm)</td>
<td>75</td>
<td>37.5</td>
</tr>
<tr>
<td>Diameter of the stopper rod (mm)</td>
<td>146</td>
<td>73</td>
</tr>
<tr>
<td>Casting speed (m/min)</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>Slab section (mm²)</td>
<td>1 250 × 80</td>
<td></td>
</tr>
<tr>
<td>Thickness of the slag layer (mm)</td>
<td>50</td>
<td>25</td>
</tr>
</tbody>
</table>
the velocity of the mixture phase in the x, y, and z directions, \( P \) is the pressure. \( \mu_{\text{eff}} \) is the effective viscosity and it is calculated by

\[
\mu_{\text{eff}} = \mu + \mu_t = \mu + \rho C_k \frac{k^2}{\varepsilon} \tag{5}
\]

where \( k, \varepsilon \) are the turbulent kinetic energy and its dissipation rate, respectively.

### 3.2. Turbulence Model

The standard \( k-\varepsilon \) model is used to describe the turbulence in the tundish during ladle change. The governing transport equations of \( k \) and \( \varepsilon \) are represented as:

\[
\frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho u_k k) = \nabla \cdot \left[ \left( \frac{\mu + \frac{\mu_t}{\sigma_k}}{\varepsilon} \right) \nabla k \right] + G_k - \rho \varepsilon \tag{6}
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho u \varepsilon) = \nabla \cdot \left[ \left( \frac{\mu + \frac{\mu_t}{\sigma_k}}{\varepsilon} \right) \nabla \varepsilon \right] + C_{1k} \frac{\varepsilon}{k} G_k - C_{2k} \rho \frac{\varepsilon^2}{k} \tag{7}
\]

where the model constants are \( C_{1k} = 1.44 \), \( C_{2k} = 1.92 \), \( \sigma_k = 1.0 \), and \( \alpha_k = 1.3 \).\(^{20} \)

### 3.3. VOF Model

The tracking of the interface between the phases is accomplished by the solution of a continuity equation for the volume fraction of each phase. For the \( q \)th phase, the equation has the following form: \(^{29} \)

\[
\frac{1}{\rho_q} \left[ \frac{\partial}{\partial t} (\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \mathbf{v}) \right] = S_{in} + \sum_{p=1}^{n} \left( m_{pq} - m_{wp} \right) \tag{8}
\]

where \( \alpha_q \) is the volume fraction of phase \( q, \rho_q \) is the density of phase \( q, m_{pq} \) is the mass transfer from phase \( q \) to phase \( p \), \( m_{wp} \) is the mass transfer from phase \( p \) to phase \( q, S_{in} \) is the source term.

The volume fraction equation will not be solved for the primary phase; the primary phase volume fraction will be computed based on the following constraint:

\[
\sum_{q=1}^{n} \alpha_q = 1 \tag{9}
\]

The density and viscosity in each cell is given by

\[
\rho = \sum_{q=1}^{n} \alpha_q \rho_q \tag{10}
\]

\[
\mu = \sum_{q=1}^{n} \alpha_q \mu_q \tag{11}
\]

A single momentum equation is solved throughout the domain and the resulting velocity field is shared among the phases. It is dependent on the volume fractions of all phases through the properties \( \rho \) and \( \mu \). The momentum equation is expressed by
\[
\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla P + \nabla \left[ \mu \left( \nabla \vec{v} + \nabla \vec{v}^T \right) \right] + \rho \vec{g} + \vec{F}
\]

where \( \vec{F} \) is a momentum source caused by the interfacial tensions at the three interfaces, steel-slag phase, slag phase-air, and steel-air. It is expressed as \(^{30}\)

\[
\vec{F} = \sum_{p=q=p \neq q} \sigma_{pq} \frac{\alpha_p \rho_p \kappa_q \nabla \alpha_q + \alpha_q \rho_q \kappa_p \nabla \alpha_p}{\frac{1}{2} (\rho_p + \rho_q)}
\]

\[
\sigma_{pq} = \left( \sigma_p^2 + \sigma_q^2 - 2 \sigma_p \sigma_q \cos \theta \right)^{1/2}
\]

where \( \sigma_p \) and \( \sigma_q \) are the surface tension of phases \( p \) and \( q \), respectively. \( \theta \) is the contact angle between phases \( p \) and \( q \).

### 3.4. Boundary and Initial Conditions

For air-steel-slag multiphase system, the incoming mass flow rate is 2.5 ton/min during steady-state casting, and it changes from 0 to 7.4 ton/min during ladle change. The inlet velocity was calculated according to the incoming mass flow rate. For the steady-state operation, the inlet velocity was set as 1.344 m/s. Then, it was changed to zero at the start of the ladle change operation until the liquid steel level decreases to the lowest level (equal to 900 mm). At this point, the inlet velocity was changed to 3.98 m/s until the liquid steel level increases to the normal operating level. Subsequently, the inlet velocity was changed again to 1.344 m/s. Due to a constant casting speed during the entire casting process, the velocity inlet boundary condition was also set at the tundish outlet, and the velocity was always kept constant at \(-1.181 \text{ m/s}\). A pressure inlet boundary was applied at the top surface of the tundish, and the pressure was set as a constant atmospheric pressure. Non-slip conditions were chosen at the walls. The enhanced wall treatment was used to model the turbulence characteristics in the near-wall region. The system was assumed to be isothermally at 1 823 K. The property parameters of liquid steel, slag phase and air employed in the simulations are presented in Table 2.

### 3.5. Computational Procedure

The three-dimensional geometric model and mesh of the tundish were created using Gambit version 2.4.6. To accurately simulate the behavior of the air-steel-slag interfaces, a refined grid was applied in the vicinity of the interfaces between the phases. The total number of mesh cells in the computational domain was approximately 1 200 000. The system of equations was solved by a commercial CFD software (Fluent version 14.0). The momentum equations were discretized using a second-order upwind scheme. The PISO scheme was used for the pressure-velocity coupling. The geo-reconstruct was selected as the volume fraction discretization scheme. The convergence criterion for the continuity, momentum, turbulent kinetic energy and its dissipation rate was set to \(10^{-4}\). The time step was 0.001 seconds. All computations were performed on a Windows 10 PC with Intel 3.4 GHz CPU and 16 GB RAM.

### 4. Results and Discussion

#### 4.1. Oil Phase Behavior

Figure 3 shows the distribution of the oil phase in the impact zone at different moments during ladle change. The lowest level, refilling time, and incoming flow rate are 450 mm, 50 seconds, and 11.2 m\(^3\)/h, respectively. Part (a) corresponds to the moment that the bath level decreased to the lowest level. During the drainage process, the incoming flow rate is zero and the oil-water flow in the impact zone is undisturbed. There is an obvious stratification between the oil phase and water. Due to a strong entry jet, the oil phase on the left side of the ladle shroud is pushed towards the right side at 5 seconds, as shown in part (b). A massive amount of oil phase is dragged into the tundish bath, forming an emulsification phenomenon. Subsequently, this phenomenon continuously develops and the entire impact zone is filled with the oil phase in part (c). Part (d) describes the moment when the bath level reached the normal operating level. The incoming flow rate was changed to 3.77 m\(^3\)/h. The oil phase and water still mix in the entire impact zone. Moreover, it is also found that a certain amount of small oil droplets flowed towards the tundish outlet during experiments. It indicates that the top slag phase in the prototype may be continuously dragged into the liquid steel during ladle change and become a source of exogenous inclusions in the slab.

Figure 4 shows the exposure behaviors of the oil and...
slag phase in the impact zone during ladle change. It can be observed that more than 50% of the oil phase in the impact zone is opened and exposed in the air. The oil phase is concentrated on the right side of the ladle shroud. This exposure phenomenon occurs continuously within the entire refilling time. Figure 4(b) corresponds to the predicted results of the slag exposure in the prototype during ladle change. A similar exposure behavior is also found for air-steel-slag multiphase system, which can be explained by the velocity fields at the steel-slag interface, as shown in Fig. 5. The liquid steel coming out from the ladle shroud firstly impinged on the bottom of the tundish, and then part of the liquid steel flowed upwards along the left wall. After reaching the steel-slag interface, the liquid steel flowed towards the weir. Due to the shear effect of the liquid steel flow, the slag layer on the left side of the ladle shroud has gradually become thinner until exposed in the air. Besides, the measured and predicted maximum exposed area fractions in the impact zone are 66.2% and 59.5%, respectively. The predicted and measured values offer a good agreement.

4.2. Effect of the Refilling Time
To diminish the oil entrainment during ladle change, the refilling times of 90, 120, and 180 seconds in the prototype are investigated and compared. Table 3 shows the corresponding refilling time and incoming flow rate in the water model. The lowest level and the shroud immersion depth are 450 mm and 200 mm, respectively. Except for the incoming flow rate during ladle change, the experimental procedures are the same as that of the refilling time of 50 seconds. Figure 6 shows the distribution of the oil phase in the impact zone at 5 seconds under different refilling times. Increasing the refilling time effectively decreases the amount of entrained oil during ladle change, especially for the refilling time of 127 seconds. These entrained oil droplets quickly float up from the tundish bath and easily reach the top oil layer in a short time. The emulsification phenomenon is also significantly diminished. When the bath level rises to the normal operating level, there are almost no oil droplets existed in the tundish bath for the case of 127 seconds refilling time, as shown in Fig. 7. However, for other refilling times, the emulsification phenomenon is still very serious. Increasing the refilling time from 50 to 85 seconds slightly improves the emulsification phenomenon. For these entrained oil droplets, they need a long time to float to the top oil layer during the subsequent steady-state casting.

Figure 8 shows the effect of the refilling time on the max-

![Image](image1.png)

**Fig. 4.** Exposure behaviors of the oil and slag phase in the impact zone during ladle change. (a) Measured; (b) Predicted. (Online version in color.)

![Image](image2.png)

**Fig. 5.** Velocity fields at the steel-slag interface in the impact zone. (Online version in color.)

![Image](image3.png)

**Fig. 6.** Distribution of the oil phase in the impact zone at 5 s under different refilling times. (a) 50 s; (b) 64 s; (c) 85 s; (d) 127 s. (Online version in color.)

### Table 3. Refilling time and incoming flow rate during ladle change.

<table>
<thead>
<tr>
<th>Prototype</th>
<th>Water model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refilling time (s)</td>
<td>Refilling time (s)</td>
</tr>
<tr>
<td>70</td>
<td>50</td>
</tr>
<tr>
<td>90</td>
<td>64</td>
</tr>
<tr>
<td>120</td>
<td>85</td>
</tr>
<tr>
<td>180</td>
<td>127</td>
</tr>
</tbody>
</table>
imum exposed area fraction of the oil phase in the impact zone during ladle change. It can be seen that a decrease in the maximum exposed area fraction of the oil phase from 66.2% to 24.1% when the refilling time increases from 50 to 127 seconds, which corresponds to a decrement of 63.6%. For the case of 127 seconds refilling time, the liquid velocity in the tundish inlet during ladle change is the smallest, which reduces considerably the shear effect of the liquid flow at the oil-water interface. Therefore, the exposed area

of the oil phase in the impact zone is decreased.

4.3. Effect of the Lowest Level

Considering the variation of the low limit steel weight in the tundish in Fig. 1, the effect of the lowest level on the oil-water flow behavior in the tundish during ladle change is investigated. The incoming flow rate and the shroud immersion depth are 11.2 m³/h and 200 mm, respectively. The shroud immersion depth represents the immersion depth of the ladle shroud during steady-state casting. Figure 9 shows the distribution of the oil phase in the impact zone at 5 seconds under different lowest levels. These lowest levels correspond to 800, 900, and 1 000 mm in the prototype, respectively. It is observed that decreasing the lowest level aggravates the oil emulsification phenomenon during ladle change, especially for the lowest level of 400 mm. The decrease in the lowest level means that the liquid reaches the oil-water interface with large kinetic energy. Thus the oil phase is easily dragged into the tundish bath. With the bath level rising, the amount of entrained oil increases. For the three lowest levels, the liquid phase in the entire impact zone becomes the oil-water emulsion as shown in Fig. 10, which indicates that for the current tundish the increase in the lowest level has little influence on reducing the slag entrainment during ladle change.

Figure 11 shows the effect of the lowest level on the maximum exposed area fraction of the oil phase in the impact zone during ladle change. Increasing the lowest level decreases the maximum exposed area of the oil phase during ladle change. When the lowest level of 400 mm is

![Graph](image)

**Fig. 8.** Effect of the refilling time on the maximum exposed area fraction of the oil phase in the impact zone during ladle change.

![Image](image)

**Fig. 7.** Distribution of the oil phase in the impact zone when the bath level reached the normal operating level under different refilling times. (a) 50 s; (b) 64 s; (c) 85 s; (d) 127 s. (Online version in color.)

![Image](image)

**Fig. 9.** Distribution of the oil phase in the impact zone at 5 s under different lowest levels. (a) 400 mm; (b) 450 mm; (c) 500 mm. (Online version in color.)
adopted, the maximum exposed area fraction is 77%, and it is decreased to 66.2% for the lowest level of 450 mm and 60.1% for the lowest level of 500 mm. Nevertheless, the area fractions above are more than 60%, which will deteriorate the steel cleanliness by the air reoxidation.

**Fig. 10.** Distribution of the oil phase in the impact zone when the bath level reached the normal operating level under different lowest levels. (a) 400 mm; (b) 450 mm; (c) 500 mm. (Online version in color.)

**Fig. 11.** Effect of the lowest level on the maximum exposed area fraction of the oil phase in the impact zone during ladle change.

**Fig. 12.** Schematic of turbulence inhibitors. (a) TI-1; (b) TI-2. (Online version in color.)

**Fig. 13.** Effect of the refilling time on the oil entrainment in the impact zone when the bath level reached the normal operating level, using turbulence inhibitors. (a) 50 s; (b) 64 s; (c) 85 s; (d) 127 s. (Online version in color.)
4.4. Effect of the Turbulence Inhibitor

The slag entrainment and exposure during ladle change are closely related to the flow pattern in the tundish, especially the flow pattern in the impact zone. These results in Figs. 3, 7 and 10 reveal that there may be a strong turbulent flow in the impact zone so that the oil phase can be easily entrained into the tundish bath. To improve the flow pattern in the impact zone, two types of turbulence inhibitors are analyzed and discussed in detail. Figure 12 shows the geometry and dimensions of the turbulence inhibitors employed in the water model. For TI-1 and TI-2, the effects of the refilling time and the lowest level on the slag entrainment and exposure in the impact zone during ladle change are investigated respectively.

Figures 13 and 14 show the effect of the refilling time and the lowest level on the oil entrainment in the impact zone during ladle change using turbulence inhibitors. It also corresponds to the moment that the bath level reached the normal operating level. The shroud immersion depth is 200 mm. It can be observed that the installation of the turbulence inhibitors significantly decreases the amount of entrained oil during ladle change. Compared with the original tundish (Figs. 7 and 10, without turbulence inhibitor), the entrained oil droplets using TI-1 are mainly located above the turbulence inhibitor. As the refilling time or the lowest level increase, the amount and depth of the oil phase

![TI-1](image1)

![TI-2](image2)

Fig. 14. Effect of the lowest level on the oil entrainment in the impact zone when the bath level reached the normal operating level, using turbulence inhibitors. (a) 400 mm; (b) 450 mm; (c) 500 mm. (Online version in color.)

![TKE](image3)

Fig. 15. Distribution of turbulent kinetic energy in the impact zone using turbulence inhibitors. (a) Original; (b) TI-1; (C) TI-2. (Online version in color.)
dragged into the tundish bath decrease. When the TI-2 is adopted, the distributions of the oil and water for the four refilling times are quite similar. The oil entrainment and emulsification phenomenon during ladle change have been effectively controlled. Only a small amount of oil phase is dragged into the tundish bath during experiments, and then this part of the oil phase rapidly float up leaving a cleaner bath.

Figure 15 shows the distribution of turbulent kinetic energy in the impact zone using turbulence inhibitors. It can be seen that the turbulence inhibitor can evidently decrease the turbulence intensity in the impact zone. For the original tundish, the turbulent kinetic energy near the free surface is $1.1 \times 10^{-3}$ m$^2$/s$^2$, and it is decreased to $7.9 \times 10^{-4}$ m$^2$/s$^2$ for TI-1 and less than $1.4 \times 10^{-4}$ m$^2$/s$^2$ for TI-2. The turbulent kinetic energies at two sides of the turbulence inhibitors are also considerably lower. For TI-1, these entrained oil droplets do not have enough kinetic energy to reach the bottom of the tundish. For TI-2, the movement of the oil phase near the free surface is relatively slow due to lower turbulent kinetic energy so that the probability of oil entrainment during ladle change is further reduced.

Figure 16 shows the velocity distribution at the steel-slag interface in the impact zone using turbulence inhibitors. Similarly, the turbulence inhibitor decreases considerably the velocity magnitudes. The maximum velocity using TI-1 is about half of that observed in the original tundish and it is decreased to 0.02 m/s using TI-2, which induces a considerable reduction in the maximum exposed area fraction during ladle change, as shown in Figs. 17 and 18. For TI-2, the maximum exposed area fractions under different refilling times and lowest levels are less than 13% and 23%, respectively. It is only 3.7% for the case of 127 seconds of refilling time. Therefore, the turbulence inhibitors not only could decrease the amount of entrained slag but also will decrease the steel reoxidation during ladle change.

5. Conclusions
The multiphase flow behavior in a single-strand continuous casting tundish during ladle change was studied using physical modeling and numerical simulation. The effects
of the refilling time, lowest operating level, and turbulence inhibitor on the slag entrainment and the steel exposure during the refilling process were investigated and discussed. The conclusions were summarized as follows.

1) For the refilling time of 70 seconds in the prototype, a massive amount of oil phase is dragged into the tundish bath during ladle change forming an emulsification phenomenon. The top oil layer is continuously opened and the maximum exposed area fraction in the impact zone is 66.2%.

2) Increasing the refilling time significantly decreases the amount of entrained oil in the impact zone during ladle change and the maximum exposed area fraction decreases from 66.2% to 24.1%. However, the increase in the lowest level has little influence on reducing the slag entrainment.

To reduce the slag entrainment and the steel exposure during ladle change, the refilling time in the prototype should be larger than 3 minutes.

3) The use of the turbulence inhibitors can considerably reduce the amount of entrained slag and the steel reoxidation during ladle change by diminishing the turbulence intensity in the impact zone and the velocity magnitude at the steel-slag interface.

4) When the TI-2 is adopted, the emulsification phenomenon during ladle change can be eliminated. As the refilling time or the lowest level increase, the maximum exposed area fractions during ladle change are less than 13% and 23%, respectively. It is only 3.7% for the case of 127 seconds of refilling time.

Acknowledgements

The authors are grateful for support from the National Science Foundation China (Grant Nos. 51704003 and 51804000), and the Natural Science Foundation of Anhui Province (Grant No. 1808085QE165).

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