Numerical Investigation of Unsteady Molten Steel Flow and Inclusion Behavior in the Tundish in the Ladle Change Period

Koichi TAKAHASHI,1)* Makoto ANDO2) and Toshio ISHI3)

1) Steel Research Laboratory, JFE Steel Corporation, 1 Kokan-cho, Fukuyama, 721-8510 Japan.
2) Steel Research Laboratory, JFE Steel Corporation, 1-1, Minamiwatarida-cho, Kawasaki-ku, Kawasaki, 210-0855 Japan.

(Received on June 6, 2013; accepted on September 25, 2013)

Prevention of defects caused by inclusions is an important technical issue in the production of high-grade steel products. In particular, inclusion removal in the continuous casting tundish is an essential technology for production of high-grade steels. It is well known that inclusion removal in the ladle change period is more difficult than during steady state casting. However, the unsteady phenomena of molten steel flow and inclusion motion in the ladle change period have not been studied in detail. To clarify these phenomena, unsteady molten steel flow and inclusion particle motion in the tundish in the ladle change period were investigated by numerical approaches. First, a numerical simulation of the unsteady molten steel flow and unsteady inclusion particle motion was carried out. As a result, it is found that the outflow rate of inclusions to the mold increases sharply immediately after the start of pouring from the new ladle. Second, flow characterization of the molten steel flow in the tundish in the ladle change period was carried out. A new method using a combined model was proposed to evaluate the flow characteristics of unsteady state tundishes in the ladle change period. The method was applied to the numerical simulation results, and showed that sharp increases in the well-mixed volume and dead volume occur simultaneously with inclusion outflow. This result indicates that flow control at the start of pouring from a new ladle is an effective approach to improve the inclusion removal performance of tundishes.

KEY WORDS: tundish; inclusion; ladle change; unsteady state; numerical simulation; computational fluid dynamics; residence time distribution; combined model.

1. Introduction

Inclusion behavior in continuous casting machines has long been studied with the aim of reducing inclusion defects in slabs. The inclusion removal performance of tundishes by floatation has been one of the important concerns in industrial continuous casting machines. Many studies of the molten steel flow and inclusion behavior in tundishes have been carried out using experimental and mathematical approaches. Among experimental approaches, water model experiments are a popular method, and in mathematical approaches, computational fluid dynamics has been widely used in recent years. Consequently, inclusions in slabs have decreased dramatically.

The combined model approach is a popular method for evaluating the flow characteristics of tundishes. Evaluation by a combined model is carried out using a tracer injection-type water model experiment or numerical simulation of tracer injection. According to the theory of the combined model, the molten steel volume in the tundish is divided into three characteristic volumes, i.e., the plug-flow volume, well-mixed volume, and dead volume. Sahai suggested a useful calculation method for combined models when evaluating molten steel flow characteristics.1,2) Sahai’s method is useful in quantitation of the flow characteristics of tundishes, and thus is commonly used by the authors.3–8) It has also been reported that the characteristic volumes, in particular the plug-flow volume, have a relation to inclusion removal performance in steady state tundishes.9,10)

Particle injection is also a popular method for direct investigation of inclusion removal performance in tundishes. In the particle injection method, the inclusion removal performance is evaluated by the ratio of particles flowing out to the mold, or the ratio of the removed particles at the top surface of the molten steel where the particles are trapped in the tundish slag layer. Many studies using numerical simulations are carried out to develop the designs of structures such as dams, weirs, turbulent inhibitors, etc.8,11–13)

Inclusions in slabs tend to increase in the ladle change period.14,15) It is well known that inclusion removal in the ladle change period is more difficult than in the steady state casting condition. Recently, inclusion control in the ladle change period has become an essential technology for producing extremely high-grade slabs with high productivity and low cost. However, it is difficult to understand the phenomena in tundishes in the ladle change period due to the extreme complexity of the unsteady flow and inclusion

* Corresponding author: E-mail: koi-takahashi@jfe-steel.co.jp
DOI: http://dx.doi.org/10.2355/isijinternational.54.304
motion during the change period. Only a few studies have been reported on molten steel flow and inclusion behavior in unsteady state tundishes such as in the ladle change period. Fan16) studied unsteady molten steel flow and unsteady inclusion phenomena at the start of molten steel pouring to the tundish using numerical simulation. Pardeshi,17) Chakraborty18) and Bölling19) studied the unsteady molten steel flow and temperature behaviors during the ladle change period by numerical simulation. However, no studies on inclusion behaviors in ladle change period have been reported by any authors. Moreover, the flow characteristics of unsteady state tundishes in the ladle change period have not been studied in detail.

In the present study, numerical investigations were carried out in order to clarify the unsteady phenomena in the tundish in the ladle change period. First, a numerical simulation of the unsteady molten steel flow and unsteady inclusion particle motion in the tundish in the ladle change period was carried out, and the time dependence of the inclusion outflow rate to the mold was then investigated. Second, a combined model was applied to the tundish in the ladle change period. A new calculation method using a combined model was proposed. The model was applied to the numerical simulation results of the tundish, and the time dependences of the characteristic volumes of the tundish in the ladle change period were obtained. Finally, the outflow rate of inclusions and the characteristic volumes in the ladle change period were compared and discussed.

2. Physical Description of Ladle Change Operation

In the ladle change operation, an empty previous ladle is replaced with a new full ladle filled with the molten steel. Because casting operation at the mold does not stop during the ladle change operation, this is an effective technique for producing slabs with high productivity and low cost.

The ladle change operation is divided into 4 phases as shown in Fig. 1. An example of the transient changes of the mass flow rate from the ladles to the tundish and the amount of molten steel in the tundish is shown in Fig. 2. The numbers in square brackets in Figs. 1 and 2 indicate the following phases. The first phase (Phase [1]) is steady state operation of the previous ladle. This phase continues until t=0 minutes, and the mass flow rate of the molten steel from the ladles is constant at 5 ton/minutes. The second phase (Phase [2]) is during ladle change, and occurs from t=0 minutes to t=3.5 minutes. In this phase, the empty previous ladle is replaced with a new ladle filled with molten steel. Although the molten steel flow from the ladle to the tundish becomes zero, the remaining molten steel in the tundish continues to be supplied to the mold at the same flow rate as in the steady state. Thus, the amount of remaining molten steel in the tundish gradually decreases. The third phase (Phase [3]) is the start of pouring from the new ladle. This starting phase occurs from t=3.5 minutes to t=4.0 minutes. The mass flow rate of molten steel from the new ladle to the tundish is increased to 40 ton/minute. The flow rate is larger than in the steady state in order to recover the standard amount of molten steel in the tundish. The fourth phase (Phase [4]) is the steady state of the new ladle. The flow rate from the new ladle to the tundish and the amount of molten steel in the tundish have both returned to the steady state values. Because the mass flow rate from the ladles to the tundish and the amount of molten steel in the tundish change dynamically in the ladle change period, the molten steel flow and inclusion particle behavior in the tundish become extremely complex during the ladle change period.

3. Mathematical Model of Molten Steel Flow and Inclusion Motion

Inclusion motion in tundishes is calculated by coupling with a molten steel flow simulation. A computational fluid
dynamics technique was employed to study the unsteady molten steel flow and inclusion motion in the ladle change period. To understand the unsteady phenomena in tundishes clearly, a simplified, rectangular tundish is adopted. The dimensions of the simplified tundish are shown in Fig. 3. The tundish serves one strand and has no flow modifiers such as dams, weirs or turbulence inhibitors. A ladle nozzle is installed at the top on one side of the tundish. Molten steel flows from the ladle to the tundish through this ladle nozzle. The tundish nozzle is located at the bottom on the other side of the tundish. The molten steel is poured from the tundish into the mold through this tundish nozzle. The flow rate of the molten steel from the ladle to the tundish is controlled using sliding nozzle. Thus the change of the hydrostatic head of the molten steel in the ladle has little effect on the molten steel flow in the tundish and the molten steel flow in the ladle is not important in this study. To simplify the problem, the ladle and mold are ignored in the simulation model.

The molten steel flow was calculated using unsteady, three dimensional computational fluid dynamics. Transient equations of mass, momentum and energy conservation are solved in the numerical simulation model. Details of the equations are reported in the reference paper, where the same governing equations are used. A finite volume method and PISO (Pressure Implicit with Split Operator) method are used to solve the coupled conservation equations. A k-epsilon turbulence model is added to the governing equations to consider the turbulent effect. The thermal convection effect is considered in the momentum conservation equation with the Boussinesq approximation. In addition, a moving mesh model is applied to the simulation model to consider the effect of the change in the molten steel level during the ladle change period. The density of the molten steel is 7050 kg/m$^3$, its viscosity is 0.005 Pa·s, and its volumetric temperature expansion coefficient is $1.135 \times 10^{-4}$ K$^{-1}$.

The inlet boundary condition is set at the ladle nozzle. The mass flow rate of the inlet boundary changes with time as shown in Fig. 2. The mass flow rate of the inlet is 5 t/min in the steady state, and changes from 0 t/min to 40 t/min during the ladle change period. The temperature of the inlet boundary is a fixed value of 1823 K. The outflow boundary condition is set at the tundish nozzle. The mass flow rate of the outlet is kept constant at 5 t/min at all times. The thermal boundary condition of the tundish walls and top surface are a fixed heat flux condition, and have values of 4000 W/m$^2$ and 40 000 W/m$^2$, respectively.

The inclusion motion is calculated using the Lagrangian particle tracking method. The turbulent dispersion effect is considered using a discrete random walk model. The same governing equations are shown in detail in the reference paper. The density of the inclusions is 3320 kg/m$^3$. To simplify the problem, the inclusions are assumed to be spherical particles with a diameter of 100 μm. The effects of agglomeration and inclusion generation in the tundish are ignored. Inclusion particles are injected from the inlet boundary at the ladle nozzle. The number density of the particles at the inlet is kept constant at 2856 particles/t-steel. The inclusion particles are carried through the tundish by the drag force of the molten steel flow and the force of gravity. Particles on the tundish walls are reflected and particles on the top surface are trapped. The rest of the injected particles reach the tundish nozzle and flow out into the mold. The number of the particles is monitored at the tundish nozzle and is used to evaluate the inclusion outflow rate, which is defined as the ratio of the number density of inclusion particles at the outlet and at the inlet. The inclusion removal performance of tundishes in the ladle change period is quantitatively evaluated by the time dependence of the inclusion outflow rate.

It should be noted that the number density of inclusions at the inlet in this numerical simulation is different from that in actual tundishes. The number density of inclusions in actual tundishes is affected by the ladle pouring condition. For example, it is known that inclusions flowing from a ladle increase at the end of the ladle pouring due to entrainment of the ladle slag. However, in the present simulation, the number density of inclusions at the inlet is assumed to be constant. When attempting to clarify the mechanism of inclusion removal in tundishes, it is desirable to separate the inclusion removal effect by flotation from other effects. This simulation model is only suitable for evaluation of the inclusion removal effect by flotation. Therefore, other effects such as slag entrainment are intentionally ignored in this study.

### 4. Calculating Method of Flow Characteristics

The combined model calculation method suggested by Sahai is commonly used for evaluation of flow characteristics in steady state tundishes. That calculation method is...
shown in Fig. 4. First, a tracer is injected from the inlet into the tundish at \( \theta = 0 \) for a short time, and the time dependence of the concentration at the outlet is monitored. A RTD curve is obtained using dimensionless time, \( \theta \), and dimensionless concentration at the outlet, \( C \).

Fluid tracers such as an aqueous solution of NaCl or dye are popular. However, particle tracers can also be used to obtain the RTD curve. When the tracer concentration at the outlet is obtained at sampling interval \( \Delta \theta \), the dimensionless concentration at the outlet is defined as shown in the following equation as a function of the outflow time \( \theta_i \).

\[
C_i = \frac{N_{out}^i \cdot V}{N_{out} \cdot Q \Delta \theta} \tag{1}
\]

Where, \( N_{out}^i \) is the number of tracer particles flowing out through the outlet during the time range \( \theta = \theta_i - 1/2 \Delta \theta - \theta_i + 1/2 \Delta \theta \). \( N_{out} \) is the total number of injected tracers at \( \theta = 0 \). The characteristic volumes are calculated from the following equations.

\[
\frac{Q_{\text{eff}}}{Q} = \sum_{0 < i < 2} C_{i}^\text{out} \cdot \Delta \theta \tag{2}
\]

\[
\theta_i = \frac{\sum_{0 < i < 2} C_{i}^\text{out} \cdot \theta_i}{\sum_{0 < i < 2} C_{i}^\text{out}} \tag{3}
\]

\[
\frac{V_d}{V} = 1 - \frac{Q_{\text{eff}}}{Q} \cdot \theta_i \tag{4}
\]

\[
\frac{V_p}{V} = \frac{V_d}{V} \cdot \frac{V}{V} \tag{5}
\]

\[
\frac{V_m}{V} = 1 - \frac{V_p}{V} \cdot \frac{V}{V} \tag{6}
\]

The common calculation method used with combined models is not applicable to tundishes in the ladle change period because the inlet flow rate changes with time. Therefore, in this study, we proposed an extended calculation method for the combined model which is applicable to the ladle change operation. The extended calculation method can be applied to problems with time-varying inlet flow rate and constant outlet flow rates. This method is illustrated in Fig. 5. In the first step, particle tracers are injected continuously from the inlet with a constant number density, as shown Fig. 5(a). All particles have injection time information. The number density of tracers flowing out at the outlet is monitored. Theoretically, the observed number density of tracers at the outlet is constant and is the same number density as that at the inlet, as shown by the solid line in Fig. 5(b). In the second step, the particles flowing out during the time range \( \theta = \theta_i - 1/2 \Delta \theta - \theta_i + 1/2 \Delta \theta \) are extracted from the particles flowing out at the outlet, as shown in Fig. 5(b) by the broken line. The extracted particles have injection time information. Therefore, in the third step, the injection time distribution corresponding to the extracted particles is reconstructed. This is shown in Fig. 5(c) by the broken line. The dimensionless tracer concentration \( C'_{in,\theta} \) of the injection
time distribution is defined by the following equation.

\[ C_{\text{m,n}}^\text{in} = \frac{N_{\text{m,n}} V}{N_{\text{out}} Q \Delta \theta} \]  \hspace{1cm} (7)

Where, \( N_{\text{out}} \) is the number of tracer particles flowing out at the outlet during the time range \( \Delta \theta \). As mentioned before, the value of \( N_{\text{out}} \) is a constant value. \( N_{\text{m,n}} \) is the number of tracer particles defined by the following two criteria: (1) The particles are poured from the ladle during the time range \( \theta_{m-1/2} \leq \theta \leq \theta_{m+1/2} \), and (2) they flow out to the mold during the time range \( \theta_{n-1/2} \leq \theta \leq \theta_{n+1/2} \). \( Q \) is the volume flow rate of the molten steel at the outlet and \( V \) is the molten steel volume in the tundish in the steady state.

The injection time distribution curve expressed by \( \theta - C'_{\text{in}} \) can be assumed to be another type of RTD curve and has the same information as conventional RTD curves. The characteristic volumes can be evaluated by Eqs. (4)–(7) and the following equations.

\[ \frac{Q}{Q} = \sum_{\theta_{m-1/2} \leq \theta} C_{\text{m,n}}^\text{in} \cdot \Delta \theta \]  \hspace{1cm} (8)

\[ \theta = \frac{\sum_{\theta_{m-1/2} \leq \theta} C_{\text{m,n}}^\text{in} \cdot (\theta - \theta_m)}{\sum_{\theta_{m-1/2} \leq \theta} C_{\text{m,n}}^\text{in}} \]  \hspace{1cm} (9)

\( \theta_{\text{min}} \) is defined as the time difference between the extraction time \( \theta_n \) and the rising point of the injection time distribution curve, as shown in Fig. 5(c). The time dependence of the characteristic volumes can be obtained by the method.

It was confirmed that the characteristic volumes calculated by the extended calculation method were equivalent to Sahai’s method in steady state problems. Thus they are a reasonable method for investigating the molten steel flow in tundishes in the ladle change period. However, it should be noted that this method is only applicable to the case of a constant outflow rate.

5. Results and Discussion

5.1. Inclusion Behavior in Ladle Change Period

Figure 6 shows the numerical simulation results of the inclusion particle distributions in the ladle change period. The numbers in square brackets correspond to the number of each phase in Figs. 1 and 2. Figure 6[1] is the particle distribution in the steady state. Many inclusion particles are distributed near the inlet. The number of inclusions gradually decreases along the downstream molten steel flow as inclusions float out in the tundish. The remainder of the particles are discharged through the outlet. These results show that the percentage of inclusions flowing out to the mold is about 8% in the case of the simplified tundish. Figure 6[2] is the particle distribution during ladle change. The density of inclusions in this phase is less than that in the steady state because the supply of inclusions from the ladle stops and the number of inclusions in the tundish gradually decreases as a result of floatation removal. Figure 6[3] is the particle distribution at the start of pouring from the new ladle. In this phase, the number density of inclusion particles near the inlet increases sharply because the inflow flow rate of the molten steel and inclusions from the ladle is higher than that in the steady state. Therefore, the high density region of inclusions quickly spreads downstream of the tundish. Finally, the inflow flow rate of the molten steel returns to the steady state and the tundish recovers a steady state.

The time dependence of the outflow rate of 100 \( \mu \)m inclusions is shown in Fig. 7. The time ranges shown by the numbers in square brackets correspond to the number of each phase in Figs. 1, 2 and 6. The outflow rate in the steady state (Phase [1]) and during ladle change (Phase [2]) is almost constant at about 8%. At the start of pouring from the new ladle (Phase [2]), the inclusion outflow rate increases sharply. Finally, the inclusion outflow rate gradually returns to the steady state, reaching the steady state value 4–5 minutes after the start of pouring from the new ladle.
It was found that the inclusion outflow to the mold increases dramatically immediately after the start of pouring from the new ladle. The similar phenomena are observed in actual machines.\textsuperscript{14,15} However, in Bolender’s experimental result,\textsuperscript{15} some defects are observed before the start of pouring of the new ladle. It means that the slag entrainment occurs in the actual machine. At the end of pouring from the old ladle, the molten steel decreases and slag layer level goes down in the ladle. Thus a certain amount of ladle slag flows into the tundish. Moreover, the slag layer in the tundish is stirred and mixed in the molten steel when the ladle nozzle of the new ladle is inserted into the molten steel in the tundish. Although it is well known that ladle and tundish slag entrainment is important factor in inclusion contamination of products during the ladle change period, the effect of slag entrainment is ignored in this simulation, and the results show only hydrodynamic effects. Thus, these results indicate that not only slag entrainment but also the unsteady flow effect are important factors contributing to increased inclusion outflow in the ladle change period.

5.2. Flow Characteristics in Ladle Change Period

The time dependences of the characteristic volumes are shown in Fig. 8. Figure 8(a) shows the plug-flow volume fraction, (b) shows the well-mixed volume fraction, and (c) shows the dead volume fraction. In the steady state (Phase [1]), the plug-flow volume fraction is 0.12, the well-mixed volume fraction is 0.56, and the dead volume fraction is 0.32. During ladle change (Phase [2]), the plug-flow volume increases. This does not mean a real increase of the plug-flow, but rather, it is the result of the change in the molten steel volume. In the combined model, the characteristic volumes are evaluated based on the steady state volume. The decrease of the molten steel volume seemingly acts as a plug flow during ladle change. At the start of pouring from the new ladle (Phase [3]), the well-mixed volume increases sharply. This indicates the existence of a strong turbulent flow caused by a large inflow. Moreover, the dead volume also increases, which means that a short-cutting flow occurs in this phase. In the steady state of the new ladle (Phase [4]), the characteristic volumes return to the steady state values. The plug flow volume returns to the steady state value at t=6 minutes (2.5 minutes after the start of pouring from the new ladle). The values of well-mixed volume and the dead volume also approach the steady state values. However, they are a little different from the steady state values at t=10 minutes (6.5 minutes after the start of pouring from the new ladle). This is because some of the molten steel in the dead region stays more than 20 minutes in the tundish. Due to the long-stay molten steel, the molten steel in the dead volume still has the unsteady effect of previous phases at the time. It takes more than 20 minutes to return the dead volume to the steady state value exactly. The well-mixed volume is affected by the slow change of the dead volume, thus it also takes more than 20 minutes to return the well-mixed volume to the steady state value exactly.

Finally, the results of inclusion behavior and flow characteristics are compared. The inclusion outflow rate increased sharply immediately after the start of pouring from the new ladle, as shown Fig. 7, which means that the inclusion removal performance deteriorates sharply at that time. At the same time, the well-mixed volume and dead volume also increase. It appears that these increases in the well-mixed volume and dead volume cause deterioration of inclusion removal performance. Two possible mechanisms can be suggested. The first mechanism is the effect of the strong turbulent flow. The well-mixed volume rises at the same time, indicating the occurrence of a strong turbulent flow caused by the strong inflow from the new ladle. The strong turbulent flow tends to disperse the inclusions in the tundish, and this prevents removal of inclusions by floatation. Thus, inclusion removal performance deteriorates. The second mechanism is the occurrence of the short-cutting flow. The dead volume rises at the same time, indicating the occurrence of a short-cutting flow in the tundish. Inclusion removal performance also deteriorates when this short-cutting flow occurs, as inclusions do not have sufficient time to float out in the tundish.

In any cases, the results indicate that flow control at the start of pouring from the new ladle is an effective approach for improving the inclusion removal performance of tundishes.

6. Conclusion

(1) An unsteady numerical simulation of the molten steel flow and inclusion motion in the tundish in the ladle change period was carried out. The time dependence of the outflow rate of 100 \( \mu \)m inclusions was investigated. The inclusion outflow rate increases sharply immediately after the start of pouring from the new ladle. This means that
inclusion removal performance deteriorates sharply.

(2) Flow characteristics were evaluated using an extended calculating method for the combined model. An extended calculation method for the combined model was newly proposed in this paper to enable evaluation of the unsteady flow characteristics in the ladle change period, and the time dependences of the characteristic volumes were obtained. The well-mixed volume and dead volume increase simultaneously with inclusion outflow. The increases in these volumes mean a strong turbulent flow and a short-cutting flow occur in the tundish.

(3) The results of inclusion behavior and flow characteristics were compared. It appears that the increases in the characteristic volumes occur in the tundish.

The well-mixed volume and dead volume increase simultaneously with inclusion outflow. The increases in these volumes mean a strong turbulent flow and a short-cutting flow occur in the tundish.

REFERENCES