Abstract: The sequential casting of slabs is a major trend in the steel industry where steel quality is the most important factor. The operating parameters have the most influence on mixing phenomenon apart from the design and shapes of the tundish and its furniture. Moreover, in industrial practice, the bath height in tundish varied with time when the ladle is changed. In the present work, the numerical simulation has been carried out to study the effect of residual volume and outflow (throughput) rate on the mixing phenomenon inside the tundish. A transient, three-dimensional two-phase model using the Volume of Fluid (VOF) method and Level Set interface tracking method has been used to investigate the intermixed grade steel formation. A comparison of the two interface tracking schemes, i.e., Geo-reconstruct and Modified HRIC (High-Resolution Interface Capturing Scheme) has also been presented. The results obtained through numerical simulation has been compared with experimental results. In a later section, the results showed that residual volume has a significant effect on the grade mixing. The mixing phenomenon in tundish is considerably influenced by the advance-pouring box (APB). Further, the outflow rate of tundish has little impact on the grade intermixing phenomenon.

Keywords: Steelmaking; tundish; intermixing; Volume of Fluid (VOF); level set

1. Introduction

The steelmaking tundish plays an important role in producing high-quality steel. In recent years, steelmaking tundish has been a reactor for liquid steel treatment. An industrial tundish is designed and operated to produce high-quality clean steel and less material loss [1–3]. The quality of solidified steel and quantity of steel scrap is an increasingly important issue in the industry. In the sequential casting process, the old ladle is replaced by a newly filled ladle. This helps in the continuous filling of tundish during each heat cycle. Further, it ensures the continuous supply of melt into the mold from the tundish. Thus, the mixing of two different grades of steel in the tundish produces intermixed grade steel. The newly mixed grade steel composition lies amid the old and the new grade [4,5]. Recent developments in the field of continuous casting have shown the need for minimizing the mixed grade steel produced in the tundish.

The operating parameters of tundish and transient melt level in tundish has a major influence on intermixed grade melt. The shapes and sizes of tundish are varied according to the need of final product [6,7], however, the operating parameters such as inflow rate, residual volume, and outflow (throughput) rate, etc., have more influence on mixing of different grades during sequential casting [8–10]. The above parameters modify the melt flow structure inside the tundish. The understanding and quantification of mixing phenomenon inside tundish is an important aspect for steelmakers. It has been reported that the bath height of melt in tundish varies during transient
operation [11,12]. Detailed examination of the mixing phenomenon in tundish was reported by Odenthal et al. [13]. They studied the transient filling sequence of the tundish and the ladle change. They studied the steady and transient casting conditions. The process of tundish filling by ladle was also numerically modeled by the Volume of Fluid (VOF) method.

The research to date has tended to focus on the steady state operating bath height of melt under numerical and experimental analysis [3–5,14,15]. Cho and Kim [16] proposed a novel mixing model for quantifying the composition distribution in solidified steel during a grade mixing. In subsequent work [17], it was reported that the model was capable of predicting the intermixed zone of various different cases, namely, bloom, slab, and thin slab casting operations. Alizadeh et al. [18] developed a numerical model to calculate the grade mixing in the tundish. They also reported that the quantity of mixed grade steel depends upon the Tundish Richardson number (Tu) dimensional number. Pieprzyca [19] studied the impact of mixing on quality of solidified steel. It was reported that improper flow and method of mixing in tundish influences the chemical and thermal heterogeneity of steel subsequently affects the quality of the cast. The detailed systematic study of mixing was reported by Muralikrishna et al. [11]. They carried out an exhaustive physical investigation on grade intermixing in a tundish. It was reported that residual volume has a significant influence on mixing. They also discussed the effect of the internal geometry of tundish on grade mixing. A correlation was developed to quantify the formation of mixed grade steel. Siddiqui and Jha [20] reported that the inflow rate has a significant impact on grade mixing in tundish during sequential castings. Cwudziński [21] carried out a numerical investigation of flow control devices in tundish to modify the hydrodynamic pattern inside the tundish. It was reported that an adverse influence of stagnant volume could be compensated by active recyle zone. Further, mixing time of alloy addition depends upon location and hydrodynamic pattern. A more comprehensive multiphase investigation on mixing was carried by Al-Harbi et al. [22]. They developed a three-dimensional multiphase numerical model to quantify the grade mixing in the tundish. The model was validated by chemical analysis of solidified slab. It was concluded that 80% of the old steel grade in the tundish can come out in the first five–six min of the mixed grade slab casting process. In further quest of understanding the hydrodynamic patterns and implementing it to minimize the mixing in the tundish, Cwudziński [21] studied the dispersion of alloys in the melt. The numerical model was developed to find the distribution of the characteristics of tundish, residence time distribution (RTD) and dispersion of alloy in one strand tundish. In a recent work by Chatterjee et al. [23], water-modeling experiments were carried out in a multi-strand tundish. The variation of dimensionless concentration-time curves (C-curves) and mixing times with different gas flow rates were studied. Further, they proposed a modified mixed model by which the proportions of different volumes were calculated. In a work of Cwudziński [24], physical and numerical experiments were carried out to understand the formation of the mixing zone during continuous casting of slabs. Buoyancy number was calculated to visualize the hydrodynamic phenomenon of mixing in the tundish. In a recent work, Krashnavtar and Mazumdar [25] have reported the influence of operating variables on grade intermixing time.

A considerable amount of literature has been published on grade mixing in tundish at constant bath height. However, there has been relatively little literature published on mixing during ladle change operation. Further, little importance has been given to the operating parameters, namely residual volume and outflow rate to understand their impact on mixing. Most of the previous research has been carried out on the single-phase numerical modeling technique. However, multi-phase numerical modeling replicates the more practical phenomenon of the industry with reasonable accuracy. Further, none have reported the impact of residual volumes and outflow rate on the grade intermixing inside the tundish by using numerical simulation methodology. Moreover, little importance has been given to comparative work on several computational methodologies related to interface tracking in the metallurgical process. Various numerical approaches can be used to simulate the multiphase problems such as Volume of Fluid (VOF) method [26], level set methods [27], front-tracking [28], marker and
cell (MAC) method [29], and phase field method [30], etc. However, the VOF method is most popular among all multiphase modeling methods.

This work is a continuation of previous research carried by Siddiqui and Jha [20]. In the present work, comparative studies of two interface tracking schemes, namely, Geo-reconstruct and modified high-resolution interface capturing (HRIC) have been carried out. The results obtained from two schemes have been compared with the experimental results. The grade mixing phenomenon in steelmaking tundish can be analyzed by multi-phase simulations because it can accurately predict the interface and mixing phenomenon. Further, a transient, 3-dimensional, two-phase model has been implemented to predict the significance of residual volume of old grade steel left in the tundish and outflow rate on the production of mixed grade steel. In addition to this, a simulation model based on two-phase flow model has been done on two configurations of tundish, i.e., bare and tundish with advance-pouring box (APB).

2. Experimental Studies

A physical model of tundish was made in the laboratory from Plexi™ glass at a 1/4 reduced scale. Figure 1 illustrates the diagram of the water-model based laboratory facility. Figure 2 shows the geometric details of a full-scale tundish and APB. The tundish was connected to the two ladles along with a flow meter and stop valves. The ladle 1 have normal water and ladle 2 have salt concentrated water, which represents two different kinds of the grade of steel. The fabricated tundish is a model of billet caster tundish that has six outlets. The outlet positions of tundish have been labeled according to the position, namely near, middle and far outlet. The experiments have been carried out by maintaining Froude’s similarity. Flow in steelmaking tundish is dominated by inertial and gravity forces, as compared to viscous forces that are relatively unimportant in such systems [31]. At the beginning of the experiment, tundish had a certain amount of residual volume of old grade from ladle 1. Once the ladle 2 was opened, two different kinds of grade (water) started mixing inside the tundish. The conductivity meters were installed at each outlet of the tundish. The instantaneous change in conductivity of exiting fluid was logged through the connected computer. The inflow rate of ladle 2 was maintained at two-times of steady state flow rate till the bath height reached the steady state operating level of the tundish. After that, inflow rate of ladle 2 was reduced to steady state condition. The F-curves (graph against conductivity of water vs. time) has been plotted at each outlet. Further, grade intermixing time was calculated for each specification of grades from F-curves. The experimental procedure has been carried out to validate the numerical model in the best possible imitation of in-plant situations. The operating parameters of tundish have been given in Table 1.

![Figure 1. Representational diagram of the water-based laboratory facility.](image-url)
3. Mathematical Modeling

Multi-phase modeling of process metallurgy problems can investigate various types of a phenomenon like molten steel-slag interface, ladle change-over, dispersion of impurities in melt, and surface level of mold, etc. The variation of tundish melt height during sequential casting can be accurately predicted through the Volume of the Fluid method.

3.1. Governing Equations

The following governing equations of mass (1) and momentum (2) have been used to model the fluid flow and mixing phenomenon inside the tundish. The equations were solved under the assumption of the isothermal condition.

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{U}) = 0 \]  
\[ \frac{\partial (\rho \vec{U})}{\partial t} + \nabla \cdot (\rho \vec{U} \vec{U}) = -\nabla p + \nabla \cdot (\tau) + \rho \vec{g} \]  

where \( p \) is the static pressure, \( \tau \) is the stress tensor, and \( \rho \vec{g} \) is gravitational body force and external body force. The new grade steel concentration was quantified, as per following equation:

\[ \frac{\partial (\rho c)}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i c) = \frac{\partial}{\partial x_i} \left( \frac{h_{\text{eff}}}{\sigma_c} \frac{\partial c}{\partial x_i} \right) \]
For turbulence modeling, two additional scalar transport equations of turbulent kinetic energy \( (k) \) and its dissipation rate energy \( (\varepsilon) \) have been solved:

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + C_h + C_b - \rho \varepsilon - Y_m \tag{4}
\]

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_H \frac{\varepsilon}{k} (G_k + C_3 \varepsilon G_b) - C_2 \rho \varepsilon^2 \tag{5}
\]

Further, the turbulent (or eddy) viscosity, \( \mu_t \), is computed by combining \( k \) and \( \varepsilon \) as:

\[
\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{6}
\]

where \( C_\mu \) is a dimensionless constant. Following values of constants for turbulent flows have been adapted from the work of Launder et al. [32].

\[
C_{1\varepsilon} = 1.44, \ C_{2\varepsilon} = 1.92, \ C_{\mu} = 0.09, \ \sigma_k = 1 \text{ and } \sigma_\varepsilon = 1.30
\]

The density and viscosity of liquid steel at melting temperature (1808 K) was considered as 7030 kg/m\(^3\) and 0.00637 Kg/m\(^{-1}\)s, respectively. Further, Reynolds stresses are computed by the following Boussinesq relationship [33]:

\[
-\rho u_i u_j' = \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \left( \rho k + u_i \frac{\partial u_k}{\partial x_k} \right) \delta_{ij} \tag{7}
\]

### 3.2. Boundary Conditions

The three-dimensional domain of tundish was discretized by unstructured tetrahedral cells (277,870 elements) for numerical computation. Only half of the tundish model has been used for the simulation due to the geometrically symmetrical fluid flow phenomenon in the domain. Mass and momentum equations were solved using the finite volume technique to simulate the two-phase simulation. The transport equation was discretized by the second-order upwind method. The pressure based segregated algorithm SIMPLE was used for transient calculation and body force due to gravity was also considered. The standard \( k-\varepsilon \) turbulence model was considered in the numerical model due to the characteristic turbulent melt flow in the tundish. In addition, the concentration equation was solved over the entire domain to accurately predict the mixing of grades. No-slip condition with zero velocity was applied at the sidewalls and the bottom of the tundish. The logarithmic law of the wall of the turbulent model has been utilized for the turbulent quantity. At the inlet boundary condition, the turbulent intensity of 2% was specified. The CFD software Ansys Fluent (version 17, Ansys, Pittsburgh, PA, USA) has been used for solving the discretized equations of transport.

### 3.3. Two-Phase Model

The multiphase problems where interface makes an important part of the research can be simulated by the VOF advection scheme. A three-dimensional numerical model was used for simulating the fluid mixing behavior in the tundish. The validation of the two-phase numerical model with experimental modeling has been carried by the reduced scale water model experiments. In this work, water and air have been considered as two immiscible incompressible fluids. The volume-averaged values of pressure and velocity have been shared by both fluid mediums. The tracking of interfaces between the phases was accomplished by the solution of a continuity equation for the volume fractions by color function \( \alpha \), where 1 and 0 correspond to two different phases and \( 0 < \alpha < 1 \) is the interface. Further, fluid advection was computed by the following transport equation:
\[ \frac{\partial F}{\partial t} + \mathbf{u} \cdot \nabla F = 0 \]  \hspace{1cm} (8)

where \( F \) is the volume fraction of the fluid in a cell and \( \mathbf{u} \) is the flow velocity vector.

The VOF method is among the methods that have capabilities to produce better interface of different phases. The VOF method uses different types of interface tracking schemes for the mass conservation. Further, a proper discretization of conservation equations is prerequisite for the accurate interface. It has been reported that lower order schemes produce smeared interface due to numerical diffusion. While higher order schemes are capable to predict better interface, the solutions through higher order scheme are unstable. In this research work, two advection schemes namely, Geo-reconstruct scheme and Modified-High Resolution Interface Capturing (HRIC) scheme have been implemented and the accuracy of the interface have been compared. In addition to this, flow advection domain was discretized by the compressive differencing scheme. Further, accurately defined interface by numerical models is dependent upon the method of discretization of the transport equation.

4. Results and Discussion

4.1. Comparison of Interface Schemes

Figure 3 shows the results obtained through above-mentioned schemes in Section 3.3 along with the experiment. The blue and red colored contours depict water and air, respectively. Figure 3a–d have been obtained from solving transport equations by using explicit discretization scheme with geo-reconstruct interface interpolation scheme. It can be seen that the Geo-reconstruct scheme was able to produce sharp details of the interface using a piecewise linear approach. This scheme is the most accurate, but time intensive. Additionally, it is observed that there are small diffused pockets in the water zone, as shown in Figure 3a–d. These pockets are developed due to entrapment of air. The contours are shown in Figure 3e–h have been obtained through a numerical model that has used the implicit discretization scheme with modified HRIC interface interpolation. The use of modified-HRIC scheme resulted in the diffused interface. This scheme calculated smeared interfaces due to numerical error caused in the computation of normalized cell value of the volume fraction. Therefore, smeared interface representation of air and water extends as the computational time advances. Figure 3i–l shows free-surface traced through laboratory experiments. It can be seen here that both interpolation schemes have close resemblance with experimental results. The free-surface height of tundish bath is accurately represented by the geo-reconstruct scheme, while the modified-HRIC scheme resulted in the smeared interface.

![Figure 3](image-url)  \hspace{1cm} Figure 3. Interface and mixing snapshot obtained by (a–d) Geo-reconstruct scheme (e–f) Modified-HRIC scheme and (i–l) experiment.
It is observed that the implicit discretization schemes are stable and are more computationally efficient. Further, smeared interfaces can be detected when low order numerical methods are applied to the calculation. In the present numerical modeling, modified High-Resolution Interface Capturing (HRIC) [34] scheme was used due to its better interface approximation and stability of the solution. The F-curves obtained from numerical models have been compared with the experimental results and further discussion on F-curves can be referred to from the authors that previously published a research article [20]. It was demonstrated that the numerical model was capable to reproduce the water-based laboratory results.

4.2. Effect of Residual Volume

In a practical situation, tundish bath height remains low when a new ladle is connected into a tundish to supply the molten metal. At this stage of the process, inflow rate from ladle shroud is usually increased in order to rapidly maintain the steady-state melt height of molten steel in a tundish. At the time of pouring of new grade steel, a significant amount of residual, old grade steel remains present in the tundish. Figure 4 shows the transient variation of tundish melt height after the ladle change-over. The important aspect of the present study is to find out the impact of remaining residual volumes on the mixing of two different grades of steel in a tundish. Numerical modeling has been carried out on three cases of residual volume fraction (RVF) in the tundish. In the first case of examination, tundish was filled up with 20% of old residual grade when new ladle was opened. Similarly, in second and third conditions, it was filled up with 40% and 60%, respectively. The inflow rate of new grade from shroud was supposed to be maintained at 1.5 times of steady-state operation. The present study has been carried out on bare tundish and tundish with APB.

![Figure 4. Variation of melt bath height in reduced scale tundish.](image)

The process of mixing of two different miscible grades in tundish occurs by displacing and diluting the old melt region. The mixing phenomenon is influenced by differences in viscosity and density. The mixing of different grades in tundish is more predominant by the macroscopic phenomenon, however, it is also impacted by the microscopic phenomenon. The mixing phenomenon of different
fluids depends upon turbulent kinetic energy. The kinetic energy of turbulent fluid exchanges between the mean and fluctuating layers of fluid. The contours of turbulent kinetic energy on a vertical plane, which is passing through the mid of tundish, has been shown in Figure 5. The predicted contours have been plotted with respect to the time of inlet of new grade fluid. In Figure 5a, it has been observed that the bottom zone of tundish was more influenced by turbulent kinetic energy. The turbulent kinetic energy at the bottom zone was produced by the shear and friction of incoming grade steel. It has also been noted that at a low fraction of residual volume, kinetic energy formation was dominant in the inlet zone of the tundish because of inlet velocity, fluid shear, and friction. This phenomenon considerably enhances the inclusion formation in tundish [9]. In contrast to this, the magnitude of turbulent kinetic energy has been noted higher at the middle outlet and far outlet at tundish with APB because of fluid shear and viscous dissipation, as shown in Figure 5b. The bath height of the tundish is depicted by arrow in Figure 5b. The change in flow behavior of incoming new grade steel has also been observed because of the placement of APB. It was seen that the value of turbulent kinetic energy has limited influence at the zone of APB, as compared with a bare tundish. The phenomenon of limited intermixing at APB zone has been possibly caused due to turbulence energy cascade and dissipation by the viscous forces at the inlet zone. It was also observed that a less amount of residual volume tundish has more mixing of the new grade in the tundish. The use of APB in tundish has modified geometry and subsequently the fluid flow pattern. It was found that fluid displacement and dispersion pattern has been modified after the use of APB.

(a) Figure 5. Cont.
the mixing phenomenon was predominant in the early stages of time. In a later stage, melt dispersion was detained for a longer period of time due to the presence of stagnant pockets of old grade. It has also been noted that the mixing phenomenon was predominant in the early stages of time. In a later stage, melt dispersion was detained for a longer period of time due to the presence of stagnant pockets of old grade. It has also been noted that the mixing phenomenon was predominant in the early stages of time. In a later stage, melt dispersion was detained for a longer period of time due to the presence of stagnant pockets of old grade. It has also been noted that the mixing phenomenon was predominant in the early stages of time. In a later stage, melt dispersion was detained for a longer period of time due to the presence of stagnant pockets of old grade. It has also been noted that the mixing phenomenon was predominant in the early stages of time. In a later stage, melt dispersion was detained for a longer period of time due to the presence of stagnant pockets of old grade. It has also been noted that the mixing phenomenon was predominant in the early stages of time. In a later stage, melt dispersion was detained for a longer period of time due to the presence of stagnant pockets of old grade. It has also been noted that the mixing phenomenon was predominant in the early stages of time. In a later stage, melt dispersion was detained for a longer period of time due to the presence of stagnant pockets of old grade.

Figures 6 and 7 show the F-curves plots that have been computed for three residual volume fractions of bare tundish and tundish with APB, respectively. It has been perceived from F-curves that the intermixing time was minimum for the lowest residual volume of tundish and maximum for highest tundish residual volume. It has also been noted that the mixing phenomenon was predominant in the early stages of time. In a later stage, melt dispersion was detained for a longer period of time due to the presence of stagnant pockets of old grade.

**Figure 5.** Contours of turbulent kinetic energy on middle plane of (a) bare tundish, and (b) tundish with APB. (The value 0 and 1 depicts old and new grade, respectively).

**Figure 6.** F-curves by varying the residual volume of reduced scale bare tundish: (a) Near outlet, (b) middle outlet, and (c) far outlet.

**Figure 7.** F-curves by varying the residual volume of reduced scale tundish with APB: (a) Near outlet, (b) middle outlet, and (c) far outlet.
Three kinds of grade specifications (stringent-stringent 20:80, stringent-lenient 10:60 and lenient-lenient 40:60) has been taken to analyze the mixing behavior in the tundish. Figure 8 shows the intermixing time for three grade specification for each outlet of the tundish. It can be seen that near outlet has minimum and far outlet has maximum grade intermixing time. It is also observed that the use of APB has considerably decreased the intermixed grade steel at each outlet when the residual volume of tundish is above 0.4. Further, the use of APB has minimized the grade mixing time, as compared to the cases of inflow rate variation.

![F-curves by varying the residual volume of reduced scale tundish with APB](image)

**Figure 8.** Intermixed amount calculated for the grade specifications from the F-curves of tundish: (a) 20:80, (b) 10:60, and (c) 40:60.

### 4.3. Effect of Outflow Rate

It has been seen that residual volume has a significant impact on grade mixing during ladle change over process. The influence of outflow rate from tundish to the mold has also been studied to analyze the effect on grade intermixing. During continuous casting, caster speed is usually varied according to the specified operating procedure. However, caster speed variations are limited due to the solidification time of slab and required quality slab. The important aspect of the present study is to find out the impact of the outflow rate on the fluid intermixing in the tundish. In the present work, three outflow rates namely 3 m/s, 4 m/s, and 5 m/s have been considered for the study. Figure 9a illustrates the contours of turbulent kinetic energy plotted on the middle plane of the bare tundish. The contours represent the instantaneous variation of turbulent kinetic energy in each case of outflow rate. It is observed that the variation of turbulent kinetic energy is insignificant at the all outlets zone. Further, the variations of turbulent kinetic energy at the upper zone are observed due to the change in bath height. Thus, a minor impact on fluids dispersion is expected from each nozzle of the tundish. In another configuration of tundish with APB, Figure 9b represents the contours of turbulent kinetic energy plotted on the middle plane of the tundish. The flow control device (APB) restricts and modifies the melt flow in other parts of the tundish. It is important to mention here that the grade dispersion was avoided by the tundish with APB. It has also been observed that the magnitude variation of turbulent kinetic energy remains trivial, and thus, not much difference in intermixed amount was predicted from each case of outflow rates. Hence, it can be said here that the grade dispersion phenomenon at different outflow rate in the tundish is somewhat similar in each case with very little variation. Figures 10 and 11 show the F-curves plotted from the instantaneous concentration data measured at each outlet of the bare tundish and without APB. The concentrations of fluids at the outlet were measured for every three cases of outflow rates. It was observed that the characteristic behavior of F-curves for both configurations of tundish remained same in all cases of outflow rates. It is noticed that the difference in mixing graph is insignificant for both cases of the tundish. The use of APB in tundish has altered the fluid dispersion phenomenon, but the outcome at each outlet indicates that the outflow rate has a minor impact over the mixing. Further, investigations in the mold can reveal the impact of outflow rate on grade intermixing.
each outlet indicates that the outflow rate has a minor impact over the mixing. Further, investigations in the mold can reveal the impact of outflow rate on grade intermixing.

Figure 9. Turbulent kinetic energy contours are shown on middle plane of (a) bare tundish, and (b) tundish having APB.

Figure 10. F-curves by varying outflow rate of bare tundish: (a) near outlet, (b) middle outlet, and (c) far outlet.
To maintain continuity in operation and improvement in the productivity, the different grades of steel are cast in single sequence by a simple ladle change over in the continuous casting process. The primary aim remains to minimize the intermixing of the grades, as intermixed grades are always considered a lower quality of casted slab. Multiphase numerical modeling has been carried out to investigate the grade mixing inside the tundish. The objective of the experiment was to quantify the intermixing phenomenon at different residual volumes and outflow (throughput) rates. A two-phase numerical model based on the VOF and Level-Set method was used to investigate the intermixing of different grades in bare tundish and tundish with APB. In first step two interface tracking schemes namely, Geo-reconstruct and Modified-HRIC schemes have been compared along with experimental results. It was found that the Geo-reconstruct produces a better interface of two different phases. However, Modified-HRIC scheme predicts the interface with reasonable accuracy with less computational effort. This research confirms previous findings on mixing and contributes to our understanding of two-phase flow under different interface tracking schemes. The results are significant in two respects namely, multi-phase modeling using VOF method along with the Level Set method and effect of operating parameters. An important finding to emerge from this study is the comparative analysis and the use of interface tracking schemes. Further, the intermixing studies have been focused on the stringent-stringent (20:80), stringent-lenient (10:60) and lenient-lenient (40:60) grades of steel. It has been observed that the residual volume fraction (RVF) plays an important role in grade formation in the tundish. It was seen that a lower fraction rapidly enhances the mixing of the new grade. While a large quantity of residual volume exaggerates the intermixing time. In addition to this, APB has been seen to reduce the intermixing and use of certain flow modifiers can help in reducing mixing by encouraging the plug flow. The effect of outflow rate has a low effect on grade mixing and little difference in intermixing time has been seen in all cases.

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References


18. Alizadeh, M.; Edris, H.; Pishevar, A. Behavior of mixed grade during the grade transition for different conditions in the slab continuous casting. *ISIJ Int.* 2008, 48, 28–37. [CrossRef]


25. Krashnavtar; Mazumdar, D. Transient, Multiphase Simulation of Grade Intermixing in a Tundish Under Constant Casting Rate and Validation Against Physical Modeling. *Jom* 2018, 70, 2139–2147. [CrossRef]


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