Mathematical Modeling of Fluid Flow Phenomena during Tundish Filling and Subsequent Initial Casting Operation in Steel Continuous Casting Process

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The purpose of this study is to develop a mathematical model to analyze the fluid flow phenomena of molten steel in the tundish during its filling stage and subsequent initial casting operation in the continuous casting process of steel. The ultimate goal is to assure smooth initial casting operation without nozzle clogging by avoiding high deposition rate of inclusion on any of the tundish outlets during tundish filling and subsequent initial casting operation.

The mathematical model is developed based on a computational fluid dynamics technique, named SOLA-MAC, and the $k$/$\varepsilon$ two-equation turbulence model. SOLA-MAC technique has the ability to handle the flow problem encountered in tundish filling, which is a transient flow problem with highly distorted free surfaces and the locations of the free surfaces are to be determined by theory. A fluid particle method is also employed in this study to analyze the distribution of inclusions in the molten steel and the extent of inclusion contamination in various strands of the continuous casting tundish. A water model that is one-fourth the scale of an actual billet continuous caster is also constructed in this study. Water model experiments are conducted to verify the accuracy and reliability of the mathematical model.

The developed model is first tested on the water model to calculate the flow pattern of water in the tundish during the very early stage of filling operation. The simulated filling patterns are compared to the water model experiments. Good consistency is observed. The model is then tested on an actual billet continuous caster with four strands to simulate the fluid flow phenomena of molten steel in the tundish during the filling and subsequent initial casting operations. Inclusion distribution and the extents of inclusion contamination among the outlets of the various strands in the tundish are also analyzed. The simulated results show that for the left half of tundish, inclusion contamination in #2 strand is significantly more severe than that in #1 strand. This is confirmed by the actual experience on the shop floor of that particular billet caster that #2 strand experiences more difficulty in clogging problem during the initial casting operation than #1 strand does.

KEY WORDS: mathematical model; tundish filling; SOLA-MAC; water model; clogging.

1. Introduction

A tundish is an intermediate vessel that taps the molten steel from the ladle and distributes it to the continuous casting molds. In order to produce clean steel and assure smooth operation, the tundish is also used as a reactor for inclusion removal in addition to its conventional role as a reservoir and distributor.

One major problem of the continuous casting process is the clogging of the outlet in the tundish bottom, which is connected to the casting mold. It is known that nozzle clogging is a progressive process with inclusions accumulated at the tundish outlets, which is the amount of inclusion deposited minus the amount of inclusions washed away by the flowing melt. As casting operation starts, the stopper rod is lifted up a certain level to allow certain passages for the molten steel to flow through the outlet to the casting mold.

As the “dirty” melt flows through the channel between the stopper rod and the outlet, the inclusions deposit on the outlet and make the channel narrower. This can be understood by the fact that the molten steel entering the tundish in the early stage of filling may carry a significant amount of inclusions. The inclusions may be caused by gas entrapment and re-oxidation of molten steel as well as refractory erosion during the early turbulent flow of molten steel in the long nozzle and tundish. During the initial casting operation, this initial dirty molten steel can deposit a large amount of inclusions in a short period of time at the outlets. With that kind of deposition rate, it is much more difficult to wash away the deposited inclusion at the outlets by the flowing molten steel through the outlets than any other stages of the casting operation. As it happens, the stopper rod needs to be lifted up higher to compensate for the flow and the casting operation becomes unstable. If the clogging
cannot be removed in time, it may even cause the casting operation to fail. However, it is very difficult and often hazardous to the operators’ safety when they try to remove the clogging manually. It is then very desirable to design and operate the continuous caster so that such problems do not occur. To tackle the problem, it is then necessary to have a good insight on the fluid flow behaviors of molten steel in the tundish during filling and subsequent initial casting operations. The fluid flow behaviors under consideration include how the molten steel flows during the filling of tundish, how the inclusions distribute in the molten steel as filling operation starts and proceeds, and how serious the outlet of each and every strand is to be contaminated by the inclusions as casting operation starts.

Reviewing the literature, rather extensive effort has been made to study the tundish problems. For the field study, most of the researches are to investigate the cleanliness of the molten steel,\(^1\) measure the temperature variation of molten steel in a particular location in the tundish,\(^2\) or measure the residence time distribution curves.\(^3\) For the physical model study, water models of full scale and reduced scale based on the Reynolds number and Froude number similarity requirement have been used to observe the flow patterns of dyed water in the acrylic tundish under various designs of flow control devices.\(^4\) A good deal of work has also been done to develop mathematical models or apply commercial computational fluid dynamics (CFD) packages to study the fluid flow and heat transfer behaviors of molten steel in the tundish. The generic models are developed based on SIMPLE scheme\(^{11-13}\) and SOLA scheme.\(^{14-15}\) The commercial packages, for example, PHOENICS,\(^{16}\) METFLO 3D,\(^{17-19}\) and CFX\(^{10}\) are available in the market. Most of these studies are, however, to study the tundish problems under steady state operation or ladle interchange period. Very few studies are addressing the problems during tundish filling. Rasmussen investigates the amount of gas entrapment in the molten steel during tundish filling and how to design the flow control devices to improve the cleanliness of the molten steel.\(^11\) Blair uses a water model to study the filling of liquid in the tundish and its corresponding gas entrapment condition.\(^20\) They do not, however, address the problem of clogging in the outlet of the tundish.

The purpose of this study is to develop a mathematical model based on the SOLA-MAC technique and the \(k\)–\(\varepsilon\) two-equation turbulence model to simulate the fluid flow phenomena of molten steel in the tundish during tundish filling and subsequent initial casting operation in the continuous casting process of steel. A fluid particle method is employed to analyze the distribution of inclusions in the molten steel and the extent of inclusion contamination in the outlets of the various strands of the continuous casting tundish. A water model is also constructed for the purpose of verification of the mathematical model. The model is then applied to an actual billet continuous caster to simulate the filling patterns and the extents of inclusion contamination in the outlets of the various strands in the tundish. The results are compared to the actual operation on the shop floor. The ultimate goal is to assure smooth initial casting operation without nozzle clogging by avoiding high deposition rate of inclusion on any of the tundish outlets during tundish filling and subsequent initial casting operation.

2. Mathematical Model

2.1. Description of the Physical Problem

A schematic diagram of a continuous casting system is shown in Fig. 1. In continuous casting process, the tundish and the ladle are first placed in positions. Then molten steel is poured into the tundish through a long nozzle, which is connected to the bottom of the ladle. The opening of the ladle is off-centered and its diameter is smaller than the inner diameter of the long nozzle. As molten steel flows through the long nozzle, protective gas is introduced into the nozzle to prevent it from re-oxidation. The molten steel flows like a column of stream, hits the bottom of the shock absorption brick, and overflows out of the brick. The molten steel is contained between two dams where openings of polygon shape are fabricated in the rear bottom of the dams. These openings are blocked by steel plates. As molten steel continues to pour into the tundish, the steel plates are melted and molten steel starts to fill all parts of the tundish. Filling is continued until molten steel reaches a certain level in the tundish. Then, stopper rods are lifted and casting operation starts.

2.2. Highlight of the Computational Fluid Dynamics Technique

Fluid Flow in a tundish during filling is highly transient; the amount and the location of the melt change rapidly. Calculation of the location of the melt must be an integral part of the computational technique employed to model the free surface problems. The SOLA-MAC technique uses a finite-difference scheme for the mathematical analysis of the fluid flow problems. Like most of the numerical techniques, it first divides the system, which is the configuration of the tundish under consideration, into a number of elements. Then a set of imaginary markers is introduced into the system to represent the location of the fluid at any instant. The velocity field of the moving fluid domain can be calculated by the application of fluid dynamics principles. Next, the markers are moved according to the calculated velocity field in order to represent the new location of the fluid domain. The procedure can be repeated from the beginning when the tundish is empty until it is filled to a predetermined height in the tundish.

2.3. Governing Differential Equations

The fluid dynamics principles used to calculate the velocity field in the flow domain are the continuity equation, momentum equation (also known as the Navier-Stokes equation), and the \(K\)–\(\varepsilon\) turbulence model equations. The equations in Cartesian coordinate system and the numerical solution procedure are previously described\(^{14-15}\) and not repeated here.

2.4. Methods of Monitoring the Variation of the Free Surface and Fluid Particles

As described in Sec. 2.2, a set of imaginary markers is introduced into the system to represent the location of the fluid at any instant. The velocity field of the moving fluid domain can be calculated by the application of fluid dynamics principles. Next, the markers are moved according to the
calculated velocity field in order to represent the new location of the fluid domain.

Several sets of imaginary markers can be introduced into the system. They can represent the fluid at a given instant or inclusion particles entering the tundish with the molten steel for different evaluation purposes. The treatments of the various fluid particles are the same. The pathline of a fluid particle can be obtained by connecting the locations of that particular particle from a starting instant to an ending instant.

3. Water Model

The water model is constructed based on an actual billet continuous caster. However, the water model is one fourth scale of the actual caster. As in the actual continuous casting operation, water is poured into the tundish through a long nozzle which is connected to the bottom of the ladle. The opening of the ladle is off-centered and its diameter is smaller than the inner diameter of the long nozzle. Water flows in the long nozzle like a column of stream, hits the bottom of the shock absorption brick, and overflows out of the brick. Water is contained between the two dams as the openings in the rear bottom of the dams are blocked by acrylcs. As water continues to pour into the tundish, the blocked acrylcs are removed at a pre-determined time and water starts to fill all parts of the tundish. Filling is continued until molten steel reaches a certain level in the tundish. Then, stopper rods are lifted and casting operation starts.

The experimental setup as well as the geometry and dimensions of the water model system is shown in Fig. 1. Basically, there are two major parts in the water model system of the billet continuous casting system. One is the ladle part and the other is the tundish part.

The ladle part includes a ladle and a long nozzle. The ladle is a cylinder of 61.4 cm in diameter and 80 cm in height. It has an opening on the bottom. The ladle opening is off-centered and 1.13 cm in diameter and connected to the long nozzle. The long nozzle is a tube of 2.13 cm in inner diameter and 30 cm long. The long nozzle is inserted into the tundish to the position where it is 5 cm above the bottom of the shock absorption brick.

The tundish part includes a tundish, a shock absorption brick, two dams, four outlet openings and four stopper rods. The tundish is approximately 130 cm long, 21.6 cm wide, and 27.85 cm high. The shock absorption brick is made of three plates. The geometry and dimensions of the three plates are shown in Fig. 1(a). The shock absorption brick is placed at the center of the tundish in the length direction. It is closer to the rear wall and 11.25 cm away from the front wall.

Fig. 1. A schematic diagram of a continuous casting system. (a) The geometries and dimensions of the ladle, tundish, dam, and impact absorption brick. (b) A top view of the tundish including the dam, impact absorption brick and casting strands.
wall of the tundish. The two dams are both 6 cm away from the shock absorption brick. Both dams have an opening, 3 cm by 3 cm, at the rear bottom of the dams. The geometry and dimensions of the two dams are also shown in Fig. 1(a).

4. Test Results and Discussions

The developed mathematical model is then tested on a water model which is one fourth scale of an actual billet continuous casting system to calculate the flow patterns during the initial filling of the tundish. The simulated filling patterns are compared with the water model observations to verify the accuracy and reliability of the mathematical model. Then, the mathematical model is tested on the actual billet continuous casting process to simulate the fluid flow phenomena of molten steel in the tundish during the filling and subsequent initial casting operations. Certain parameters related to the smoothness of the initial casting operation are derived from the calculated results of the simulations and compared with the actual experience on the shop floor for that particular billet caster.

4.1. Simulated Results and Experimental Observations for the Water Model System

To simulate the fluid flow phenomena during the initial filling of the tundish of the water model system, the geometry of the tundish and the lower section of the long nozzle are first constructed. In the tundish, the impact absorption brick, the dams, the openings in the rear bottom of the dams, and the stopper rods are all included. Then, a mesh system of 57 by 21 by 21 is generated for the modeled system. The total number of elements is 25,137. As described in Section 2.1, the inlet is designated at the (29, 14, 20) element, which is located at the center of the lower section of the nozzle, 15 cm below the bottom of the ladle. The inlet velocity is a variable, depending on the water level in the ladle. The inlet velocity at the beginning of the tundish filling is around 390 cm/sec. Water flows into the tundish and is confined between the two dams as the dam openings are sealed. At 4 seconds after the tundish filling starts, the openings at the rear bottom of the two dams are open and water starts to fill all parts of the tundish. The duration of four seconds is chosen to correspond to the melting of the steel plates which are used to seal the openings of the dams and force the initial molten steel to accumulate between the two dams in the tundish.

The mathematical model for the water model system is run for five seconds to simulate its filling patterns with the initial conditions and boundary conditions described in the previous section. Water is filling the area between the two dams in the tundish and the lower section of the long nozzle for the first four seconds. The simulated results during this stage are not shown here since they are not the major concerns in this study. The flow simulation is executed for one more second after the dam openings are open. The flow patterns of water filling the outer sections of the tundish are then shown for four instants. Since the tundish is symmetrical along the center of the long nozzle, the filling patterns are only shown for the outer section of the left half of the tundish.

The simulated results are demonstrated in two ways. One is to use the vector plots of the velocity profiles of the water for the three bottom layers of the tundish due to the fact that the dam openings are three layers high and only these three layers are being filled in this stage. The three layers are designated as k2, k3, and k4, with k2 being the lowest layer in the tundish, k3 being on top of k2, and k4 on top of k3 as shown in Figure 2(a). The top view of the velocity profiles of water in the three layers at t=4.2, 4.5, 4.8, and 5 sec. are shown in Figs. 2(b)–2(e). The arrows denote the direction and magnitude of the water flow. From the flow patterns, it can be seen that fluid exits from the dam opening and flows along the rear wall of the tundish as the dam is first open. As the flow is hindered by the rear wall, it is diverted towards the center of the left half of the tundish. The fluid proceeds and reaches the outlet of the #2 strand, which is closed by a stopper rod. As fluid hits the front wall, it is split into two streams. One stream flows towards the outlet of the #1 strand, which is closed by a stopper rod. The second stream turns back and flows towards the outlet of the #2 strand. It is also clearly seen that fluid spreads faster in the lower layers, especially in the k2 layer. The second way to demonstrate the flow patterns is by plotting the configurations of the fluid domains. The element in the k2 layer is filled with light blue color if it contains fluid in it. Regular blue color is used for the elements in the k3 layer while deep blue color is used for the elements in the k4 layer. Then the fluid configurations are plotted as they are viewed from the top of the tundish at the same four instants as in Figs. 2(b)–2(e). These plots are shown on the right hand side of Fig. 3.

After the work of numerical simulation is completed, a water model experiment is then conducted. The flow conditions in the water model are controlled to match those in the mathematical model. The experimental observations are shown on the left hand side of Fig. 3. The fluid evolution can be clearly seen from the pictures. The lighter areas in the fluid domain in the pictures can be easily visualized as the areas where fluid occupies the bottom layer while upper layers do not contain fluid. The darker areas then show the areas where fluid exists in the bottom layer as well as the upper layers. In these pictures, it can be seen that fluid quickly exits from the opening and flows along the rear wall of the tundish as the seal is lifted off. As the flow is hindered by the rear wall, it is diverted towards the center of the tundish. Fluids first reaches the outlet of the #2 strand. As fluid reaches the front wall of the tundish, it is slightly accumulated and split into two streams. One stream flows to the left and reaches the outlet of the #1 strand. The second stream turns to the right to fill the side area around #2 strand of the tundish. Fluid accumulation is rather obvious on the left part of the tundish and gradually propagates to the right. When the simulated flow configurations are compared to those of the water model experiments, satisfactory consistency is observed.

4.2. Simulated Results for an Actual Billet Continuous Casting Process

As the mathematical model is verified with the water model experiments, it is then applied to simulate the flow conditions during the filling and subsequent initial casting operation of an actual billet continuous caster. The geome-
Fig. 2. (a) A 3-D parametric view of the tundish and the positions of the various horizontal layers.  
(b)–(e): Velocity profiles of water in the three bottom layers of the tundish for four instants after fluid is allowed to fill the outer sections of the tundish.
try and dimensions of the actual billet continuous caster are described in Sec. 2.1 and shown in Fig. 1. Again, the geometry of the tundish and the lower section of the long nozzle are constructed and a mesh system of 57 by 21 by 21 is generated. The inlet is again designated at the (29, 14, 20) element, which is located at the center of the lower section of the long nozzle, 60 cm below the bottom of the ladle. The inlet velocity is a variable that is calculated based on the fluid level in the ladle and inner diameter of the ladle. The inlet velocity at the beginning of the tundish filling is around 780 cm/sec. Molten steel is flown into the tundish and stored between the two dams at a temperature of 1620°C. It has a superheat of 45°C to avoid premature freezing at the tundish outlet. Four seconds after the filling starts, the dam openings are open. The choice of four seconds is an observed data from the shop floor operation of the actual tundish as the steel plates that are used to seal the openings of the dam are melted. Molten steel keeps filling the tundish up to 100 sec. After that, the four stopper rods are lifted and casting operation is started.

To start the casting operation, the stopper rods are lifted as shown in Fig. 4(a). The space between the lifted stopper rod and the outlet of the strand, which is designated as “A” in Fig. 4(b), becomes an open space for the fluid flow. For
the mathematical model, it is simplified as the transition zone in Fig. 4(c). The transition zone of 10 cm in height is designated as wall area before casting operation is started. As casting operation starts, the transition zone is re-designated as flow channel and the center element on the bottom of the transition zone is re-designated from a wall element to an outlet element. The outlet velocity is around 324 cm/sec, which is calculated based on the flow level in the tundish.

The mathematical model is then executed to simulate the fluid flow condition of molten steel in the tundish for the filling stage (the first 100 sec) and a short period after the casting starts (approximately 20 sec). Figure 5 shows the flow condition of the molten steel in the initial storage area between the two dams. The fluid particles which represent the earliest entering melt at 4 sec after pouring are seen to flow mostly towards #1 strand. In Figs. 8(b) and 8(c), the fluid particles which represent the early melt are seen to flow more towards #1 strand than #2 strand. However, the extent of flow to #1 strand is decreasing while the extent of flow to #2 strand is increasing. As shown in Fig. 8(d), most of the fluid particles are seen to flow towards #2 strand after 7 sec.

It should be noted that the scales of the velocity vector are different from those of Fig. 5 for better visualization of the flow conditions. It can be clearly seen that a large circulation develops around the outlet of #2 strand and a smaller circulation also forms near the same outlet. This phenomenon is known to have the detrimental effect of collecting most of the dirty particles, which enter the tundish with the molten steel in the early stage of the filling operation. Figure 6 shows the velocity profile of molten steel in the k3 layer at 101 sec after the casting operation starts. It can be seen that a large circulation is formed around the outlet of #2 strand. As expected, the flow speeds are seen to increase rapidly near the outlet and point towards the outlets. This is because the elements surrounding the outlet must provide the molten steel, which flows out vertically at a speed of 324 cm/sec. Therefore; the horizontal speeds at these elements would have to be rather high.

To evaluate the smoothness of the initial casting operation, the extents of initial dirty melt which may be sucked into the various strands are analyzed in two different ways. It is known that the main source of inclusions that cause problems in the initial casting operation is from the molten steel entering the tundish in the early stage during the filling of tundish. The first way to evaluate the extents of contamination through the various strands is to analyze how the early not-so-clean melt flows during the tundish filling operation. This is done by analyzing the pathlines of fluid particles which represent the early melt. Four sets of fluid particles are used in this study with eight particles in each set. They are all placed in the lowest layer, k2 layer, in the tundish. The four set of particles are placed at 21.9, 49.4, 98.8, 133.1 cm away from the dam. These particles are placed in the tundish at various instants during the tundish filling operation and allowed to flow along with the flow field of the molten steel. The pathline of each and every particle is drawn. The results are shown in Fig. 8. In Fig. 8(a), the fluid particles which represent the earliest entering melt at 4 sec, are seen to flow mostly towards #1 strand. In Figs. 8(b) and 8(c), the fluid particles which represent the entering melt at 5 sec and 6 sec, are seen to flow more towards #1 strand than #2 strand. However, the extent of flow to #1 strand is decreasing while the extent of flow to #2 strand is increasing. As shown in Fig. 8(d), most of the fluid particles are seen to flow towards #2 strand after 7 sec.

Fig. 5. The fluid flow condition of molten steel in the initial storage area between the two dams. (a) Velocity vector plots, (b) Color contour plots.

Fig. 6. Velocity profile of molten steel in the k3 layer right above the strand outlets at time=100 sec, which is right after the tundish is filled to the appropriate height and ready for casting operation the scales are different from those of Fig. 5.

Fig. 7. Velocity profile of molten steel in the k3 layer at time=101 sec, which is right after the casting operation is started.
except those particles initially near the #1 strand. With the development of the circulations around and near the #2 strand as shown in Fig. 6, it is obvious that the #2 strand is much more vulnerable to clogging during the initial casting operation.

The second way to evaluate the extent of contamination in the various strands is by placing one particle in every element of the dam opening at $t=4$ sec., as the dam opening is just open. There are nine elements in the opening and therefore nine particles are used. These particles enter the tundish along with the molten steel and they are meant to represent the inclusions carried into the tundish by the early entering melt. For every new time step, a new set of nine particles is added in the dam opening. The addition of these “dirty” particles are continued for each time step up to 10 sec. However, these particles are allowed to flow along with the molten steel in the tundish up to 100 sec as the tundish filling is completed. **Figure 9** shows the distribution of these “dirty” particles in the specified lower layers at $t=100$ sec as the tundish filling is just completed. For easier visualization, the tundish is again cut horizontally into a number of layers as shown in Fig. 9(a), with the positions of k2, k3, k4, k5, k9, and K10 layers. From the k3 layer up to the k5 layer, more “dirty” particles are near the #2 and #3 strands than the #1 and #4 strands as shown in Figures 9(c) to 9(g). In the k7 layer and the k10 layer, more “dirty” particles are near the #1 and #4 strands than the #2 and #3 strands. It can then be reasoned that the “dirty” particles carried into the tundish are dispersed in the tundish. However, the “dirty” particles near the #2 and #3 strands tend to hang around in the lower level while those near the #1 and #4 strands tend to float to the upper level in the tundish. It again means that #2 and #3 strands are more prone to the clogging problem in the initial casting operation. An even more direct evaluation of the inclusion contamination among the various strands is conducted by continuing the flow simulation after the tundish is filled and casting operation starts. The numbers of “dirty” particles flowing through the four strands are counted from the time when the stopper rods are lifted and casting operation is just started at time equals to 100 sec up to around 120 sec. The result of these “dirty” particle counts for #1 strand and #2 strand is shown in **Fig. 10**. The “dirty” particles exiting through #2 strand is about three times as many as those exiting through #1 strand. For the first second during the initial casting operation, the number of “dirty” particles, which are supposed to be the dirtiest among the “dirty” particles, exiting through #2 strand is about three times as many as those exiting through #1 strand. The fact that #2 strand experiences more difficulty in clogging during the initial casting operation than #1 strand is confirmed by the shop floor experience of that particular billet caster under the specific

![Pathlines of fluid particles representing molten steel at various instants in the early stage of tundish filling. (a) Fluid particles representing molten steel at 4 sec, (b) Fluid particles representing molten steel at 5 sec, (c) Fluid particles representing molten steel at 6 sec, (d) Fluid particles representing molten steel at 7 sec.](image-url)
design and operation condition as taken in this study.

5. Conclusion

A mathematical model has been developed to analyze the fluid flow phenomena of molten steel in the tundish during tundish filling and subsequent initial casting operation in the continuous casting process of steel. The mathematical model is based on the SOLA-MAC technique and the $k$–$\varepsilon$ two-equation turbulence model. A water model which is one fourth the scale of an actual billet continuous caster is also constructed.

The mathematical model is first tested on the water model system to calculate the flow pattern of water in the tundish during the very early stage of filling operation. When the simulated filling patterns are compared with the water model experiments, good consistency is observed. The mathematical model is then tested on an actual billet continuous caster to simulate the fluid flow phenomena of molten steel in the tundish during the filling and subsequent initial casting operations. Inclusion distribution and the amount of dirty particles exiting through the outlets of the various strands in the tundish are also analyzed by a fluid particle method. The simulated results show that for the left half of tundish, inclusion contamination near #2 strand is significantly more severe than that in #1 strand. This is confirmed by the actual experience on the shop floor that #2 strand experiences more difficulty in clogging during the initial casting operation than #1 strand does.

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Nomenclature

- $A_i$: Weighted Area of cell, $i=1–8$ (cm$^2$)
- $A_{ladle}$: Bottom area of ladle (cm$^2$)
- $A_{out}$: Opening area of the ladle (cm$^2$)
- $A_{outlet}$: Opening area of the tundish (cm$^2$)
- $C_d$: Discharge coefficient
- $g$: Gravitational constant (cm/s$^2$)
- $K$: Turbulent kinetic energy (cm$^2$/s$^2$)
- $n$: Old time term
- $n+1$: New time term
- $q_{casting}$: Casting quantity (cm$^3$/s)
- $t$: Time (s)
- $u_i$: Velocity of near cell, $i=1–8$ (cm/s)
- $v_i$: Velocity of near cell, $i=1–8$ (cm/s)
- $V'_i$: Weighted volume of cell, $i=1–8$ (cm$^3$)
- $V_{casting}$: Casting speed (cm/s)
- $V_{inlet}$: Velocity at inlet (cm/s)
- $V_{outlet}$: Velocity at outlet (cm/s)
- $w_i$: Velocity of near cell, $i=1–8$ (cm/s)
- $\varepsilon$: Dissipation rate of turbulence Kinetic energy (cm$^2$/s$^3$)
- $\delta$: Time interval (s)
- $\Delta h_0$: Initial height of ladle melt (cm)
- $\Delta h$: Height of ladle melt (cm)
- $\Delta x$: Cell spacing in $X$ direction (cm)
- $\Delta y$: Cell spacing in $y$ direction (cm)
- $\Delta z$: Cell spacing in $z$ direction (cm)
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