

Modeling of Inclusion Capture in a Steel Slab Caster with Vertical Section and Bending

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Abstract: Particles in molten steel, including argon-gas bubbles, slag droplets, and non-metallic inclusions, are removed into the surface-slag layer or captured by the solidifying steel-shell during continuous steel casting. Captured particles often become serious defects in the final steel product, so understanding particle-capture mechanisms is important for steel quality. Slab casters often have a straight mold and upper-strand prior to a curved lower-strand. The present work investigates particle capture in such a caster using computational modeling with a standard $k-\epsilon$ model for molten-steel flow, a discrete phase model for inclusion transport, and an advanced capture criterion for inclusion entrapment and engulfment into the steel shell. A new postprocessing methodology is presented and applied to predict inclusion-capture rates in commercial cast product. The locations and size distributions of particles captured into the shell, and actual capture rates are quantified. The model predictions are validated with ultrasonic-test plant measurements of the locations of large particles captured in a steel slab. The results reveal how large-inclusion capture accumulates in the beginning of the curved strand, leading to a capture band in the slab inside radius. Finally, the capture fractions and locations due to all capture mechanisms are compared for different inclusion sizes, and the implications are discussed.

Keywords: steels; continuous casting; inclusions; entrapment; engulfment; defects

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1. Introduction

During continuous casting particles in the molten steel include argon gas bubbles injected to prevent nozzle clogging [1,2], slag droplets entrained into the molten steel pool due to abnormal high surface velocity and / or severe surface instability [3,4], and non-metallic inclusions flowing into the mold cavity from upstream processes such as the ladle, tundish, and transfer operations [5]. These particles are transported by the molten steel flow, to be removed into the surface slag layer, or to be entrapped by the solidifying steel shell in the mold and strand regions.

Particles entering the mold may be safely removed into the surface slag layers or captured into the steel shell in three different ways: 1) entrapment by subsurface hooks near the top surface [6,7], 2) entrapment by moving in between solidifying dendrites according to the Primary Dendrite Arm Spacing (PDAS), or 3) engulfment by balancing at the steel shell solidification front and then being surrounded by the growing dendrites. Once particles are captured into the steel shell, and are not removed by scale formation or scarfing processes, they eventually become defects, such as blisters and / or slivers in the final steel products after annealing and rolling processes [8]. Thus, it is important to understand the complex phenomena of particle transport and capture in the mold and

strand regions, and to minimize such defects by controlling the system geometry, fluid flow, and casting conditions.

To understand the transport and capture of particles in continuous steel casting, several studies on the complex phenomena have been conducted. Many researchers have applied the simple capture model which assumes particle capture if the particle simply touches the steel shell front [9–12]. Some use the simple capture model only for particles smaller than the PDAS, which are easily entrapped between growing dendrites [13]. Other models specify capture when particles move into a specified range of solid fraction of steel [14,15]. However, large particles are much more difficult to capture than small particles, especially those larger than the PDAS, and are captured only if they rest stationary on the dendritic solidification front for long enough to become surrounded and engulfed by the growing dendrites [16]. Thus, many simple capture model simulations likely overpredict particle capture [9–12,14,15].

Thomas et al. developed an advanced particle capture criterion which is able to simulate both entrapment of small particles between PDAS and engulfment of large particles by growing dendrites. Particles small enough to fit between the primary dendrite arms are entrapped according to the simple criterion. Particles larger than the PDAS are predicted to be engulfed only when they touch the dendritic interface and all of the forces acting on the particle are balanced [17,18]. The force balance includes the effect of surface tension gradient force, which pushes particles towards the solidification front [17–20]. This criterion has been validated with a benchmark experiment [21] and applied to accurately predict the capture of particles during steel continuous casting according to validation with several different sets of plant measurements [17,18,22,23]. For example, the number and location of captured argon bubbles predicted by this criterion with a large eddy simulation model was validated via step-milling measurements, which also revealed the importance of turbulence on the particle behavior near the steel shell front [22]. Recently, a steady-state turbulent flow model with the advanced capture criterion predicted argon gas bubble capture in a curved strand that reasonably matched Ultrasonic Testing (UT) measurements [23].

In previous studies using the advanced capture criterion, several simulations have been conducted to investigate particle capture defects in commercial continuous steel casters [17,18,22,23]. The critical cross-flow velocity range for particle capture has been quantified according to particle type, PDAS, solidification front velocity, sulfur concentration, and solidification front angle [17]. Biased flow caused by a slide-gate flow control was revealed to cause more bubble capture on the inner radius, especially near the nozzle [18]. Furthermore, static-electromagnetic braking systems were shown to reduce the penetration depth of the jet, leading to less bubbles sent down the narrow face deep into the strand, and less particle capture [22].

These previous works used continuous particle injection to predict particle distributions in the cast product. This requires high computation cost to obtain sufficient numbers of rare large particles for reasonable statistical accuracy, even in the short domains used in these studies [18,22]. The computational burden becomes much larger with high-resolution turbulence models such as Large Eddy Simulation (LES) [22]. For parametric studies, there is a need for more computationally efficient approaches to model particle distributions in the slab product [10,23]. Furthermore, the exact particle locations have not been compared with plant measurements, and previous investigations did not report on the distinction between engulfment and entrapment mechanisms. Finally, previous work has simulated only the top few meters of vertical casters and curved casters. However, many modern casters are constructed with a vertical upper section, followed by bending to a conventional curved lower machine, seeking to lessen particle capture, especially in the inner radius (IR) of the wide face (WF) of the strand, where it is most problematic.

The present work applies the advanced particle-capture criterion [17,18] with a standard k - ϵ turbulent fluid-flow model and a particle transport model, to investigate the transport and capture of large inclusion particles during continuous casting of steel slabs

in a commercial caster with a vertical mold and upper section and a curved lower strand, using a 9.5m-long strand domain. In addition, a new computationally efficient methodology of postprocessing the particle capture predictions is introduced to predict actual rates of the inclusion capture in the steel slab. The model prediction of the inclusion capture in the huge domain caster is compared directly with plant measurements of the number and location of large particles captured in a steel slab sample from a commercial caster. Finally, the capture fractions and mechanisms of inclusion capture including both entrapment and engulfment are quantified according to inclusion size, considering molten steel velocity, inclusion velocity and PDAS.

2. Computational Modeling

Three-dimensional computational modeling of turbulent molten-steel flow, and transport and capture of inclusions in continuous steel casting with the process conditions given in Table 1 is conducted using a Reynolds-Averaged Navier-Stokes equation (RANS) based standard k - ε model, a Lagrangian Discrete Phase Model (DPM), and the advanced particle-capture criterion. A new methodology of postprocessing the simulated particle capture is applied to quantify the actual rate of particle capture in steel slabs and slab samples.

Table 1. Caster dimensions and process conditions.

Caster dimensions	
Nozzle port area	85 mm (width) × 85 mm (height)
Nozzle port angle	−25° (downward) at both top and bottom
Mold thickness	250 mm
Mold width (w)	1100 mm
Strand geometry	Straight mold and upper strand, curved lower strand
Domain length	0.68 m above meniscus is modeled 9.5 m below meniscus is modeled
Process conditions	
Steel flow rate	330 LPM (2.3 tonne/min)
Casting speed	1.2 m/min (20 mm/sec)
Tundish height	1200 mm
Steel grade	Low carbon steel: carbon 0.04 wt%
Shell thickness profile	2.6 mm/sec ^{0.5}
Slide-gate open-area fraction	40.36%
Slide-gate opening direction	90° (movement towards outer radius wide face)
Inclusion size range (diameter)	10–1000 µm: DPM particle injection condition
Submergence depth of nozzle	185 mm

2.1. Turbulent Molten-Steel Flow: RANS Standard k - ε Model

Steady-state turbulent flow of molten steel in the nozzle, mold, and upper strand is modeled using a RANS-based standard k - ε model. Mass conservation of the molten steel is calculated as by solving:

$$\frac{\partial}{\partial x_i}(\rho u_i) = S_{shell, mass} \quad (1)$$

where ρ is molten steel density, u is molten steel velocity, and $S_{shell, mass}$ is a mass sink term, which is applied to the cells at the steel shell front, to account for solidification of the molten steel which should cross that domain boundary, as explained elsewhere [21,24,25].

Momentum conservation of the molten steel flow is satisfied by solving:

$$\frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial p^*}{\partial x_i} + \frac{\partial}{\partial x_j} \left[(\mu + \mu_t) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + S_{shell, mom, i} \quad (2)$$

where p^* is modified pressure $p + 2/3 \rho k$, p is gauge static pressure, μ is dynamic viscosity, and μ_t is turbulent viscosity calculated from turbulent kinetic energy, k , and its dissipation rate, ε , according to two additional transport equations described below [26]. Finally, $S_{shell,mom,i}$ is a momentum sink term to account for steel solidification, and is only applied to the cells at the steel shell front together with $S_{shell,mass}$ [21,24,25].

The two additional scalar transport equations of turbulent kinetic energy, k and its dissipation rate, ε are solved to model turbulence:

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon + S_{shell,k} \quad (3)$$

$$\frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} G_k - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_{shell,\varepsilon} \quad (4)$$

where σ_k and σ_ε are turbulent Prandtl numbers associated with k and ε , 1.0 and 1.3 respectively, G_k is generation of turbulent kinetic energy due to mean velocity gradients, $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are standard constants, 1.44 and 1.92 respectively, and finally, $S_{shell,k}$ and $S_{shell,\varepsilon}$ are sink terms for turbulent kinetic energy and turbulent kinetic energy dissipation rate to account for steel solidification [27].

Flow boundary conditions include constant velocity at the nozzle inlet and a stationary wall with a no slip condition at the interface between the molten steel pool and the slag layer at the mold top surface. Domain sides represent the solidification front, where zero velocity is imposed, and the mass and momentum sources remove steel to reproduce a boundary condition of the downward casting speed, as explained elsewhere [21,24,25]. The domain bottom where steel flows continuously into the lower strand is treated as a pressure outlet in Ansys Fluent [28].

2.2. Inclusion Particle Transport: DPM Model

The transport of large particles, such as argon bubbles, entrained mold slag, or non-metallic oxide inclusions such as alumina, is modeled by solving discrete phase model (DPM) transport equation to track each individual particle. The DPM model evaluates a force balance on each particle considering the four forces including drag force (F_D), buoyancy/gravity force (F_B), and virtual mass force (F_V), and pressure gradient force (F_P) from the first term in the right side of Equation (5) as follows:

$$\begin{aligned} \frac{1}{6} \pi d^3 \rho_p \frac{du_p}{dt} &= F_D + F_B + F_V + F_P \\ &= \frac{1}{8} \pi \rho d^2 C_d |u - u_p| (u_p - u) + \frac{1}{6} \pi d^3 g (\rho_p - \rho) + \frac{1}{12} \pi d^3 \rho \frac{d}{dt} (u - u_p) \\ &\quad + \frac{1}{6} \pi \rho d^3 \frac{Du}{Dt} \end{aligned} \quad (5)$$

where d is inclusion diameter, ρ_p is inclusion density, u_p is inclusion velocity, C_d is drag coefficient [29], g is gravitational acceleration. In addition, the discrete random walk model is incorporated in the DPM model to include the effect of turbulence on the particle dispersion [28]. The random walk velocity changes in proportion to the square root of the local turbulent kinetic energy according to the local eddy lifetime [28].

2.3. Inclusion Particle Capture: Advanced Capture Criterion

The advanced capture criterion [17,18] simulates particle capture via two mechanisms: 1) small particle entrapment between PDAS and 2) large particle engulfment by dendrites growing to surround particles suspended at the solidification. For the engulfment mechanism, a force balance on each particle at the steel shell front is evaluated to consider if a particle touching the solidification will be suspended, or whether it will be

washed back into the flow. This force balance considers the four forces used by the DPM model (F_D , F_B , F_V , and F_P) in Equation (5), and four additional forces including the lift force, lubrication force, Van der Waals force, and surface tension gradient force.

The lift force, F_L is calculated as follows:

$$F_L = -\frac{9}{4\pi}\mu(d)^2U_S\text{sgn}(G)\left[\frac{|G|}{\nu}\right]^{1/2}J \quad (6)$$

where $U_S = u_l - u_{p,l}$, u_l and $u_{p,l}$ are instantaneous streamwise velocities for the molten steel and inclusion, respectively, $G = \frac{du_l}{dy}$, ν is kinematic viscosity, $J(\epsilon) = 0.6765[1 + \tanh(2.5\log_{10}\epsilon + 0.191)][0.667 + \tanh(6\epsilon - 1.92)]$, and $\epsilon = \text{sgn}(G)\frac{\sqrt{|G|\nu}}{U_S}$

The lubrication force, F_{Lub} , due to the pressure-driven flow in the thin gap between the particle and the steel shell front, is given as follows:

$$F_{Lub} = 6\pi\mu u_{sol}\frac{(R_p)^2}{h_0}\left(\frac{r_{tip}}{r_{tip} + R_p}\right)^2 \quad (7)$$

where u_{sol} is the solidification front velocity, h_0 is the distance between the dendrite tip and particle, R_p is the particle radius, and r_{tip} is the dendrite tip radius.

The Van der Waals force between the particle and the steel shell front tip, F_I is calculated as follows:

$$F_I = 2\pi\Delta\sigma_0\frac{r_{tip}R_p}{r_{tip} + R_p}\left(\frac{a_0}{h_0}\right)^2 \quad (8)$$

where, $\Delta\sigma_0 = \sigma_{sp} - \sigma_{sl} - \sigma_{pl}$, σ_{sp} , σ_{sl} , and σ_{pl} are the surface tensions for steel shell/particle, steel shell/molten steel, and particle/molten steel, respectively, and a_0 is the diameter of a molten steel atom.

The surface tension gradient force, F_{Grad} is calculated using Equation (9):

$$F_{Grad} = -\frac{m\beta\pi R_p}{\xi^2}\left\{\frac{(\xi^2 - (R_p)^2)}{\beta}\ln\left[\frac{(\xi + R_p)[\alpha(\xi - R_p) + \beta]}{(\xi - R_p)[\alpha(\xi + R_p) + \beta]}\right] + \frac{2R_p}{\alpha} - \frac{\beta}{\alpha^2}\ln\left[\frac{\alpha(\xi + R_p) + \beta}{\alpha(\xi - R_p) + \beta}\right]\right\} \quad (9)$$

where $\xi = R_p + r_{tip} + h_0$, $\alpha = 1 + nC_0$, $\beta = (C^* - C_0)n r_{tip}$, C^* and C_0 are the elevated sulfur content at the dendrite tip interface due to segregation, and the average sulfur content in the bulk of the steel, respectively. m and n are empirical constants. More details of the forces are given in previous work [17,18].

A flow chart of the particle capture modeling methodology is given in Figure 1. At the top surface boundary, the fate of particles touching the interface between liquid slag layer and molten steel pool is determined. The current model simply simulates these particles as being safely removed into the slag layer. At the solidification front boundary, particles are modeled as being captured by entrapment between the primary dendrite arms if they touch the solidifying steel shell, and are smaller than the PDAS of the steel alloy. The fate of particles larger than the PDAS is decided from the results of the force balance calculation as given in Figure 1. The particle is captured by engulfment if the resultant force acting on the particle pushes it towards the steel shell. If the forces do not balance, and the particle is calculated to rotate about the dendrite tip, then the particle

drifts back to the flow field due to the random walk velocity and continues to be tracked. Particles exiting the bottom domain boundary with the flowing liquid into the lower strand are assumed to be captured eventually [17,18].

Unoptimized casting conditions with low casting speed and wide mold width often produce abnormal low surface velocity leading to the formation of deep subsurface hooks which tend to capture particles near the slab surface. In such cases of low surface flow, the methodology should include a hook capture model [30] as well as the advanced capture criterion [17,18]. The current work focuses on internal particle capture, which is measured in steel slab samples manufactured from the plant, so hook capture and other surface defects are not considered.

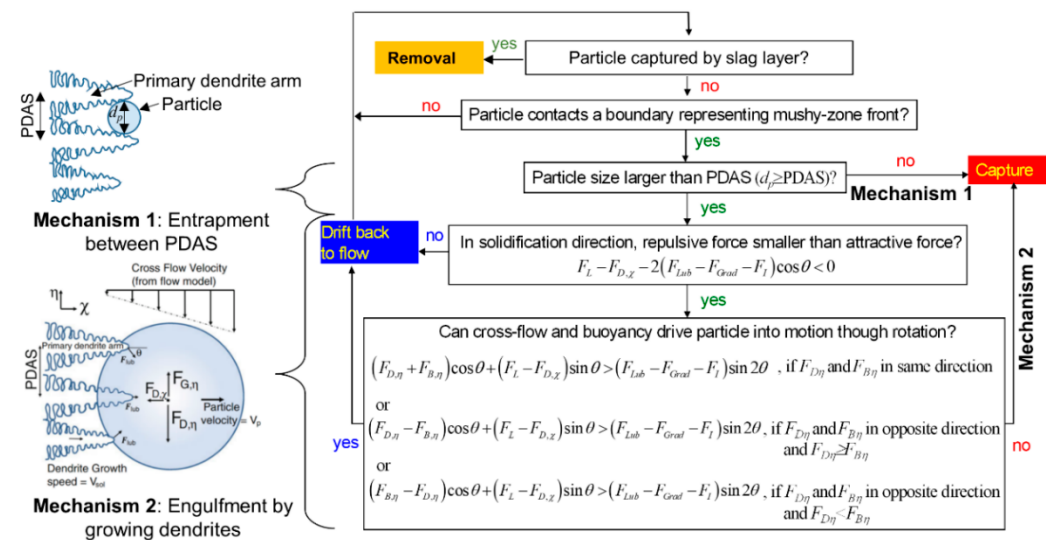


Figure 1. Flow chart of the advanced capture criterion modelling methodology.

2.4. Numerical Details

The computational domain includes the slide-gate, Submerged Entry Nozzle (SEN), two nozzle ports, mold, and strand regions, including straight, bender, and curved parts, as shown in Figure 2. This three-dimensional domain consists of 1.64 million hexahedral cells. The steel shell thickness profile is estimated from the measured breakout shell and PDAS profile is calculated [23], and the profiles are given in Figure 3. These profiles are used in creating the mold and strand domain, which includes only the liquid pool.

Inclusions are injected into the domain for an arbitrary time period, 5 s, with a size distribution, $n_{pre,i}$, consisting of 10,000 of each size group, i of 10, 20, 50, 100, 200, 300, 500, and 1000 μm diameter. This number was chosen based on the previous finding that at least 2500 particles are needed to achieve reliable statistical variations ($\pm 3\%$ accuracy) and that 10,000 particles is better for accurate predictions of particle removal [10,17]. A time period of 390 s is simulated to allow sufficient time for the transport, capture, or removal of all inclusions in the domain.

The governing equations are discretized using the finite volume method according to the computational domain in Figure 2 and solved using the commercial package, Ansys Fluent [28]. The sink terms to account for steel solidification [25] and the advanced capture criterion modeling methodology [17] are implemented with separate C-code based User-Defined Functions in Fluent [28], as explained previously. Convergence is defined when all scaled residuals are stably reduced smaller than 10^{-4} . The steady fluid flow simulation took 3 h, and the transient transport and capture of 80,000 inclusions required 47.5 h of wall-clock computer time to calculate up to 395 s of simulation time using a parallel computing workstation with 30 cores (Dell Precision Tower 7910 with Intel(R) Xeon(R) E5-2620 v4 2.10 GHz CPU, 128 GB RAM).

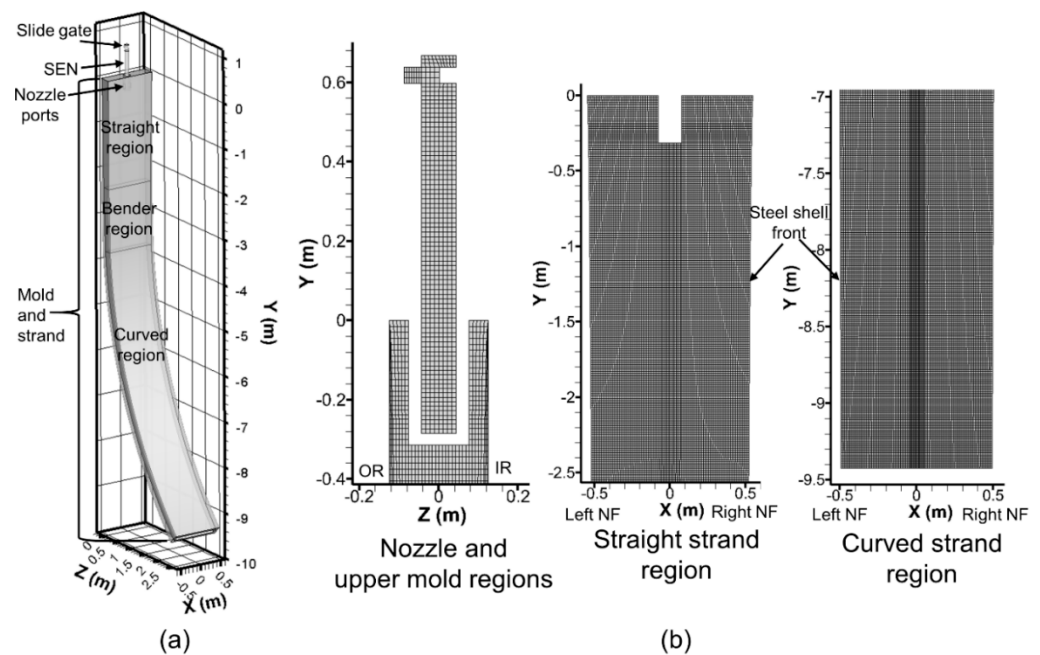


Figure 2. Three-dimensional (a) domain and (b) mesh of the computational models of the continuous caster nozzle and strand.

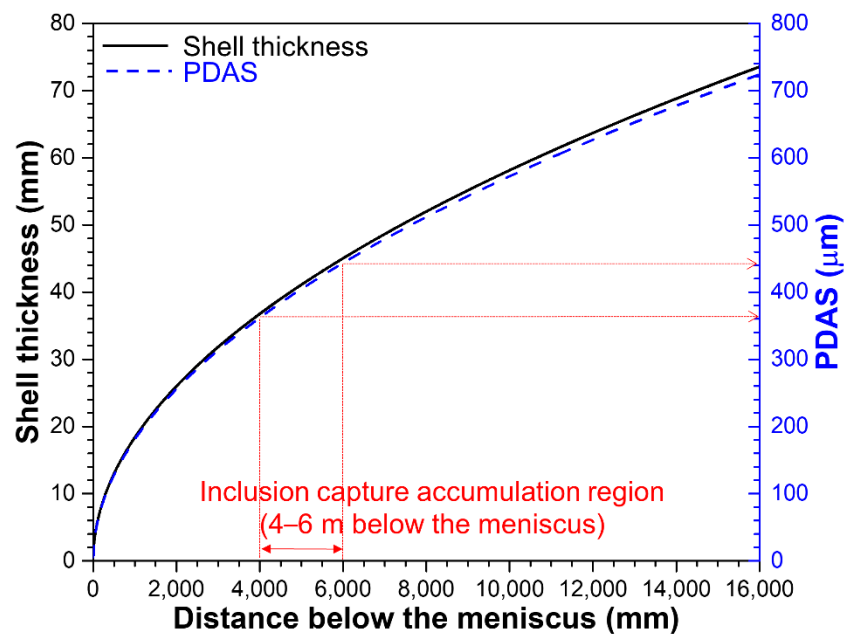


Figure 3. Solidifying steel shell thickness and Primary Dendrite Arm Spacing (PDAS) profiles.

2.5. Postprocessing of Capture Model Results: Capture Rates in Slab Product

To compare model predictions of inclusion capture with plant measurements performed on as-cast steel slabs, produced during steady casting conditions while inclusions continuously flow into the mold and strand regions through the nozzle from the upstream processes, a new methodology of postprocessing the results of the particle capture simulation is introduced and applied in this work.

First, the actual inclusion injection rate into the caster is estimated. In this work, the alumina inclusion particle content distribution measured in a tundish sample [31,32], C_j (ppm), as shown in Figure 4a, is converted into mass fractions, F_j as follows:

$$F_j = \frac{C_j}{\sum_{j=1}^{20} C_j} \quad (10)$$

where j is 20 size groups covering the inclusion diameter range of equivalent solid alumina spheres from 1 to 40 μm .

Second, as shown in Figure 4b, the mass fraction distribution of inclusions in the tundish is converted into a Rosin-Rammler distribution with calibrated mean diameter (11 μm) and calibrated spread parameter (1.01), based on a nonlinear regression.

Next, the injection rate of each inclusion size, $q_{int,j}$ is calculated from the mass fraction distribution using Equation (11) as follows:

$$q_{int,j} = \frac{F_j \times \sum_{j=1}^{20} C_j \times Q_s}{m_j} \quad (11)$$

where Q_s is molten steel flow rate (kg/s) and m_j is mass of each inclusion ($\frac{\pi d^3 \rho_p}{6}$). To estimate the number of large inclusions (typically missed in the small tundish sample), the injection rate from Equation (11) is then extrapolated (linearly in a logarithmic scale) from the measured diameter range of 1–40 μm to the wider diameter range of 1–1000 μm , which is considered in the particle capture simulation, as shown in Figure 4c. This extrapolation is based on a fractal distribution which is usually observed in steady-state inclusion distributions [33–35]. To include other sources of inclusions such as slag droplets and reoxidation, the extrapolation is expanded from 24 to 100 ppm, which corresponds to an increase in Total Oxygen (T.O.) content from 11 to 47 ppm, which is within the range of T.O. contents measured in previous tundish studies [36–38].

Finally, the capture rate of inclusions of each size predicted to be found in an as-cast steel slab sample, $R_{c,i}$ (#/s) is calculated from the corresponding number of inclusions captured in the simulation, $N_{c,i}$ (#) as follows:

$$R_{c,i} = S_i N_{c,i} = \frac{t_{mea}}{t_{pre,i}} N_{c,i} = \frac{(l/u_{cast})}{(n_{pre,i}/q_{int,i})} N_{c,i} \quad (12)$$

where S_i is the time scale factor, which is the ratio of the casting time that the steel slab sample is exposed to particle capture while in the caster, t_{mea} , to the effective injection time of the model, $t_{pre,i}$. The sample casting time, t_{mea} , depends simply on the length of the sample in the casting direction, l and the casting speed, u_{cast} . The effective injection time of the model, $t_{pre,i}$ depends on the number of injected inclusions with size i , $n_{pre,i}$ and the injection rate, $q_{int,i}$. This postprocessing enables easy prediction of actual capture rates of all inclusion sizes in the real steel-slab sample without excessive simulation times, while maintaining sufficiently large numbers of particles to achieve statistical accuracy, even for the rare but important large particles.

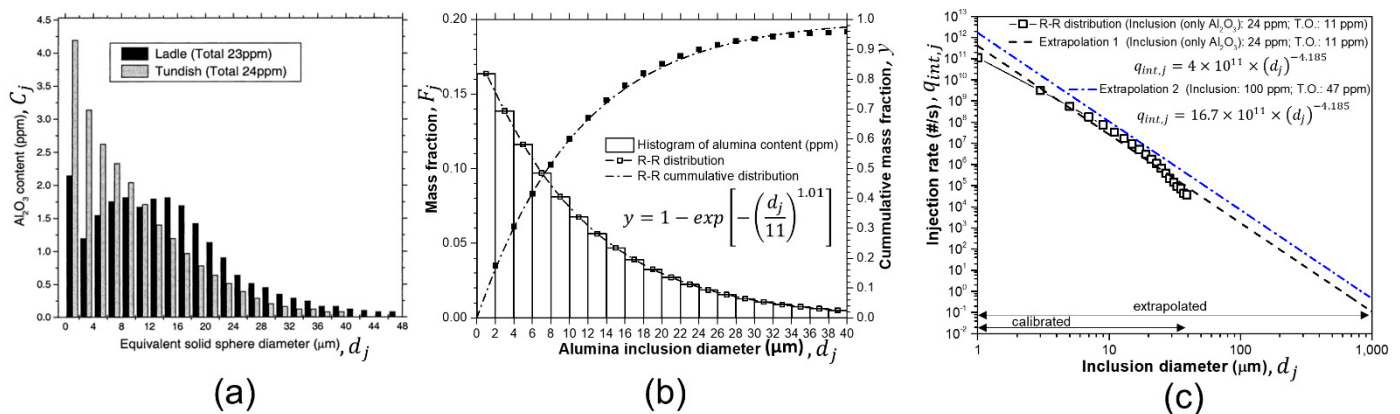


Figure 4. Injected distribution of inclusions: (a) measured in tundish [32], (b) transformed Rosin-Rammler size distribution of the tundish, and (c) injection rate into the nozzle.

3. Plant Measurements of Particle Capture: Ultrasonic Testing

Ultrasonic Testing (UT) measurements [39,40] were conducted to measure the locations and numbers of large particles entrapped in a low-carbon aluminum-killed steel ($[\text{C}] = 0.04\%$, $[\text{Al}] < 0.01\%$) full-section sample of a typical commercial continuous-cast slab (width: 1195 mm, thickness: 250 mm, and length: 103 mm) at a casting speed of 1.6 m/min, which is slightly faster than the simulation conditions. The ultrasonic waves are transmitted from one Narrow Face (NF) to the other NF through the width direction of the steel slab sample. This enabled the projection of the locations of the captured particles onto a view of the narrow face. The projected image reveals all captured-particle locations along the directions of the slab thickness and cast length. The locations of the captured particles were then quantified using the software program, WebPlotDigitizer [41]. Only large particles can be detected by this method.

The large captured inclusions appear to have originated from upstream processes, which included steelmaking in a Basic Oxygen Furnace (BOF), deoxidation with top addition of aluminum cones, refining in an Ruhrstahl Heraeus (RH) degasser, Ar-gas stirring in a 300 tonne ladle, flow through a tundish, and possible reoxidation or slag entrainment during transfer operations, before entering the caster through the slide-gate nozzle. They could be dendritic alumina from reoxidation, alumina clusters from collisions between deoxidation products, or most likely: entrained ladle slag or tundish slag. Such slag inclusions contain various nonmetallic oxides which lowers their solidification temperature, so they are liquid in the molten steel and adopt a spherical shape during transport and capture in the continuous caster.

4. Results and Discussion

The computational models were applied to quantify the molten steel flow, and the transport and capture of inclusions in the mold and straight-curved strand during continuous slab casting for typical slab-casting conditions, and validated by comparison with the plant measurements. The locations and size distributions of the captured inclusions into the solidifying steel shell are quantified according to distance below the meniscus, distance from the slab surface, and PDAS profile. The removal and capture fractions of inclusions in different strand regions, and the mechanisms of inclusion capture into the steel shell are investigated.

4.1. Molten-Steel Flow in Mold and Strand

Figure 5 shows the flow pattern and velocity contours of the molten steel at the center middle plane between Inside Radius (IR) and Outside Radius (OR), in the plane one quarter of the distance across the mold width ($w/4$), midway between the mold center and

right NF, and in the w/8 plane near the right NF in the mold and strand region including the straight, bender and curved parts. The jet from each nozzle port impinges on the NF region ~ 0.5 m below the meniscus. After hitting the NF, the jet splits into upward flows toward the top surface and downward flows going deep into the strand. This behavior of the jet generates a classic double-roll pattern including an upper roll extending from the meniscus to the point of jet impingement (~ 0.5 m below the meniscus) and a lower roll extending from the jet impingement region down to ~ 4.5 m below the meniscus.

As shown in Figure 6a, the upper roll produces a surface velocity of 0.185 m/s midway between the nozzle and the narrow face, which is not expected to cause any significant slag entrainment problems related to dragging slag droplets into the molten steel pool. However, this surface velocity is slightly lower than the recommended window of safe operation (0.2–0.4 m/s) [42], so there might be issues with meniscus hook formation and particle capture. The slidegate, with its 90-degree orientation perpendicular to the wide faces, produces strong swirling flow exiting the nozzle ports (Figure 6b) which causes the jets to impinge stronger on the IR WF than on the OR WF, as indicated by the velocity contours in Figure 6c,d.

The lower roll takes the particle-laden molten steel flow deep into the strand, with downward velocity exceeding 0.3 m/s just below the mold. Some particles are transported with this flow deep into the strand, increasing the chances of particle capture defects. Near the inside radius (IR) of the shell, the downward velocity slows to only 0.01–0.02 m/s (green color range in the contour), in the entrance of the curved parts, as shown in Figure 5c. This corresponds to a region of low velocity on the IR WF, caused by the strand geometry transition from the bending region to the curved region of the strand.

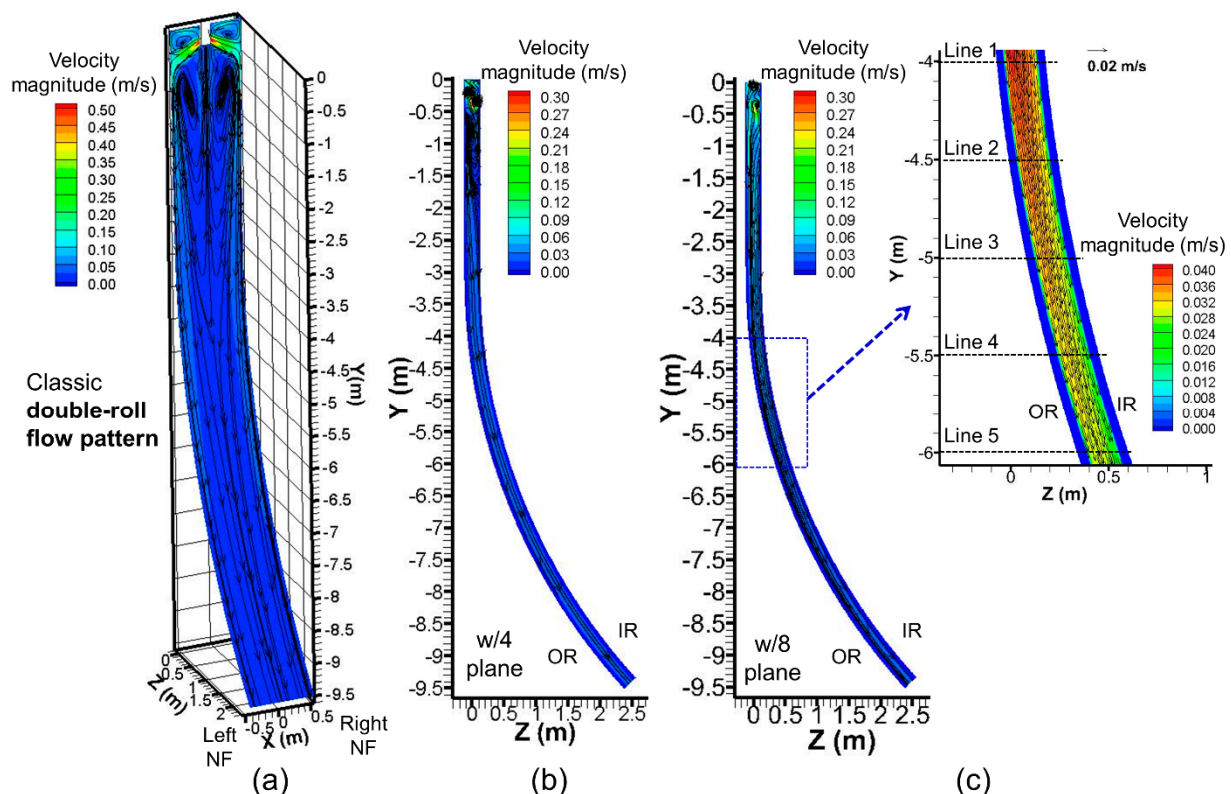


Figure 5. Flow pattern and velocity at (a) the center middle-plane (3D view between IR and OR), (b) the w/4 plane (side view midway between SEN and NF), and (c) the w/8 plane (side view near NF) in the strand with close-up.

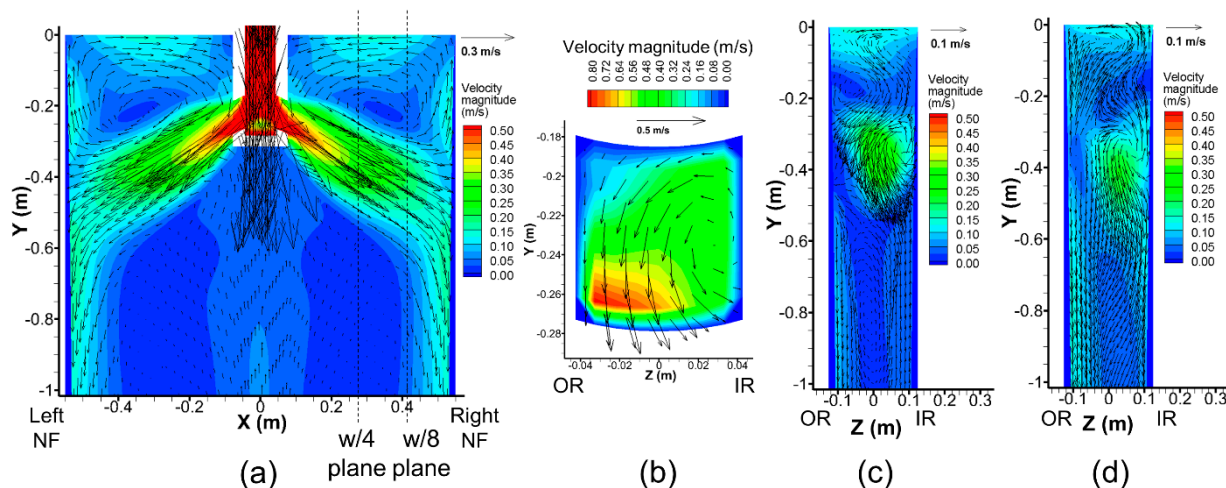


Figure 6. Jet behavior at (a) the center middle-plane (front view between IR and OR), (b) the nozzle port, (c) the w/4 plane (side view midway between SEN and NF), and (d) the w/8 plane (side view near NF) in the mold.

4.2. Distribution of Captured Inclusions

Inclusions injected through the nozzle into the mold are carried by the turbulent jets, and eventually reach either the slag layer at the mold top surface or the solidifying steel shell on the Wide Faces (WFs) and NFs. Inclusions reaching the slag layer are removed. On the other hand, many inclusions, including most small inclusions, are transported to the steel shell front, where they become entrapped between primary dendrites into the solidifying shell, as shown in Figures 7–9. Inclusions that are captured deep into the strand become internal defects in the final product which cannot be removed.

Figure 7 shows the locations of the inclusions captured into the steel shell on the WF IR, by inclusion size. In the mold region, more inclusions are captured on the WF OR shell than on the WF IR, as shown in Figures 7 and 8. This is likely because the high-velocity jets from the nozzle ports flow closer to the IR shell (Figure 6), which produces a washing effect that lessens capture in the IR shell in the mold.

Below the straight region, more inclusions are captured on the WF IR shell, due to the buoyancy effect that alters the trajectories of inclusions upwards towards the IR, as suggested in many previous works [14,15,40]. Compared to the number of the inclusions captured per unit area into the steel shell on WFs, the NF steel shell captures less inclusions below the straight region, as shown in Figure 9. This is due to the larger distance that the inclusions need to be transported to reach the NF shell.

Inclusion capture decreases with distance deeper into the caster, especially for large particles, owing to the general buoyancy of inclusions. However, larger captured inclusions, with sizes from 200 to 300 μm , tend to accumulate at 4–6 m below the meniscus on the WF IR. This region is near to the beginning of the curved part of the lower strand. This accumulation leads to a band of inclusion capture found about $\frac{1}{4}$ of the slab thickness beneath the WF IR.

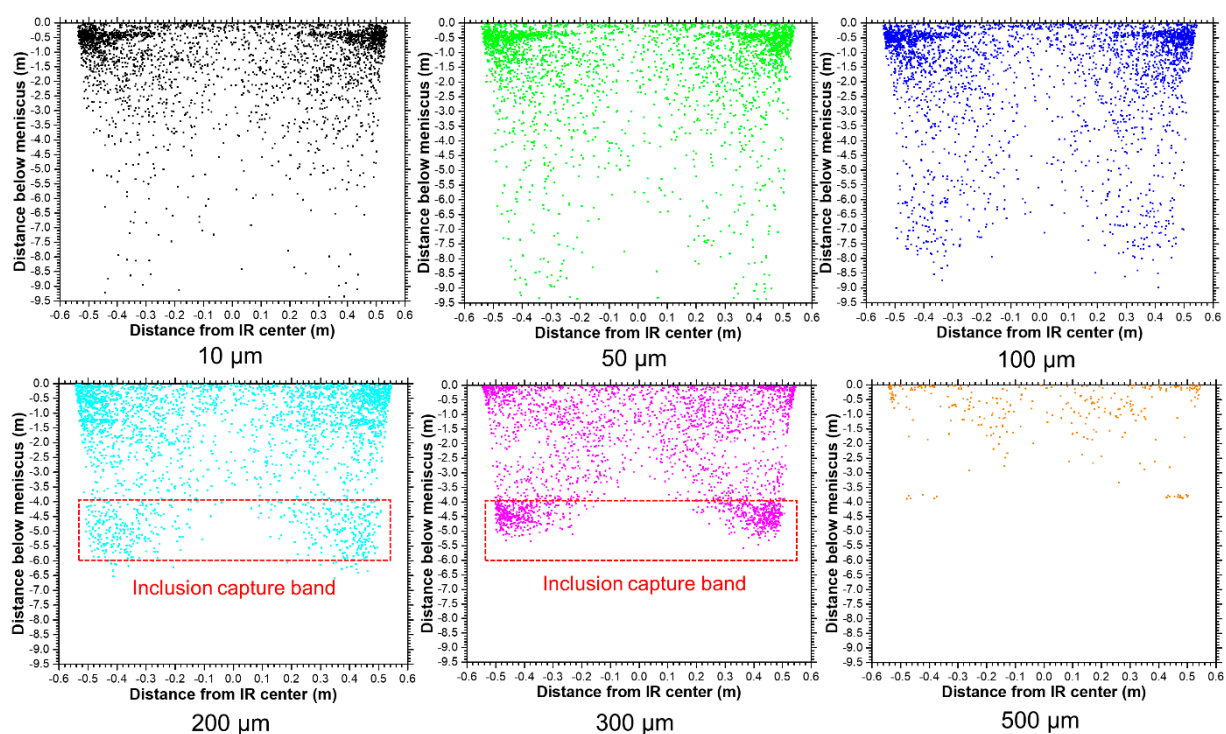


Figure 7. Inclusion capture locations on the IR shell, by inclusion size (front view).

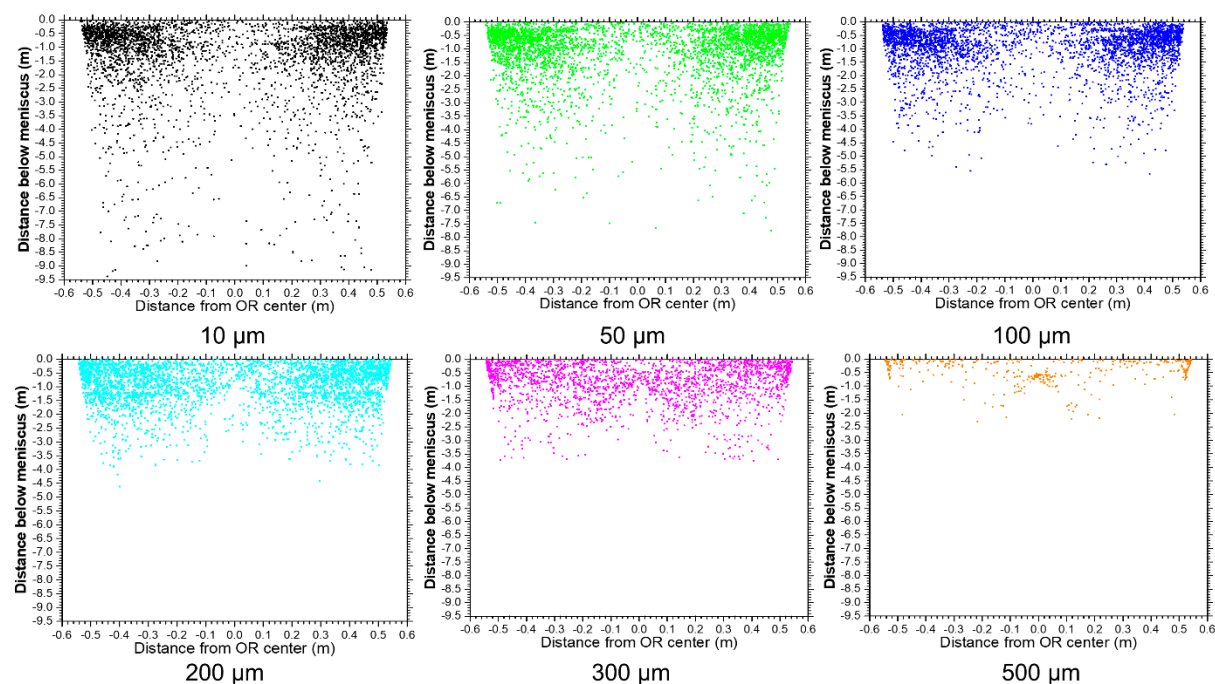


Figure 8. Inclusion capture locations on the OR shell, by inclusion size (front view).

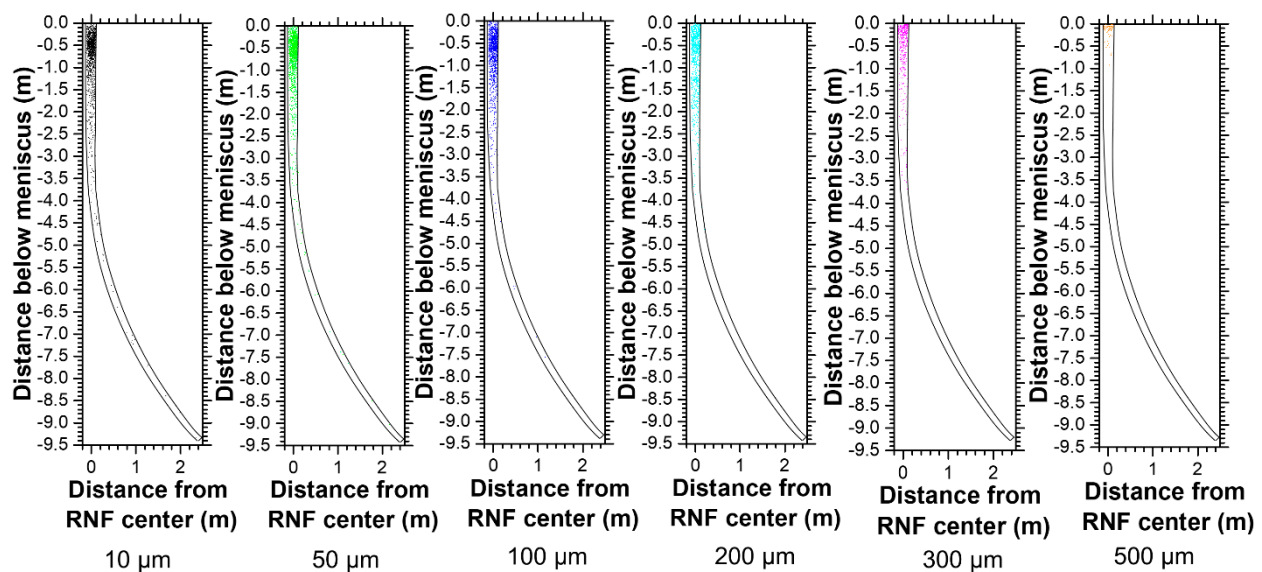


Figure 9. Inclusion capture locations on the right NF shell, by inclusion size (side view).

The distribution of inclusions captured into the steel shell by distance below the strand surface (into the strand thickness) and by the corresponding distance below the meniscus is given on each strand face as histograms in Figure 10. There is a large peak of inclusion capture at ~500 mm below the meniscus, about halfway down the mold where the jet impinges (Figure 6). In addition, there is a second smaller peak of large inclusion capture on the IR shell which matches the capture accumulation region (4–6 m below the meniscus), shown in Figure 7.

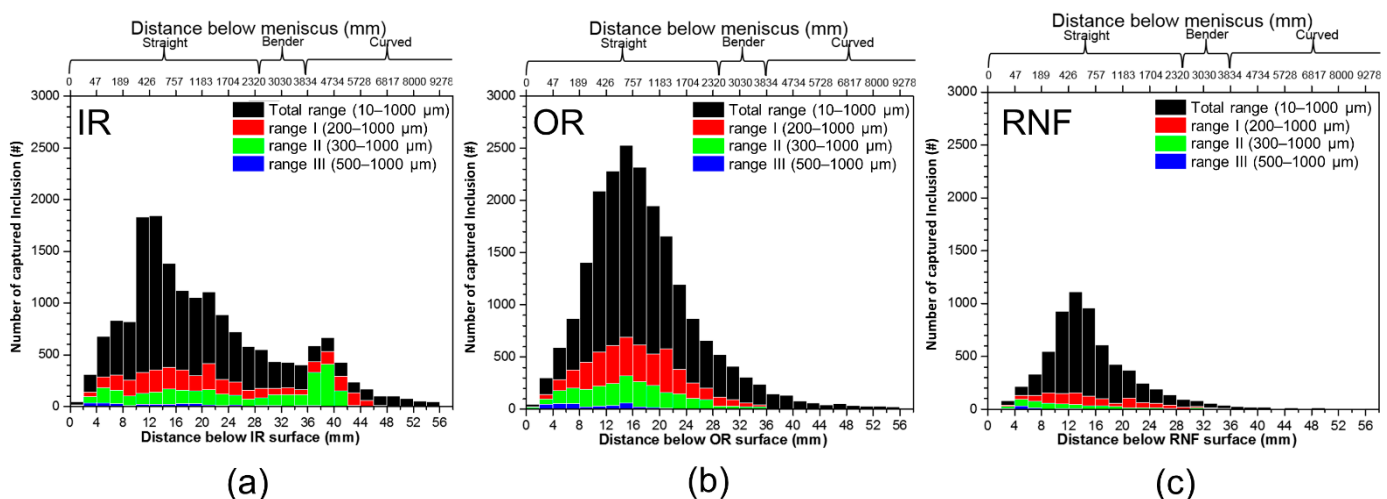


Figure 10. Histograms of modeled inclusion capture locations on (a) the IR shell, (b) the OR shell, and (c) the right NF shell.

These inclusion capture distributions are predicted using the advanced capture criterion. Figure 11 shows the inclusion capture locations at the surface slag (upper frames), IR steel shell (middle frames), and OR steel shell (lower frames). This figure also compares the predictions using the advanced capture criterion (left frames) with those from the simple capture criterion, where all inclusions touching the steel shell front are captured (right frames). As expected, fewer inclusions are captured into the steel shell (more inclusion removal into the surface slag) using the advanced capture criterion. Furthermore, results with the advanced criterion also show the accumulation band of inclusion capture 4–6 m below the meniscus, near the entrance of the curved part of the IR strand, (Figure 11a

middle frame), which is frequently observed in curved strand casting. This capture band is not predicted by the simple capture criterion.

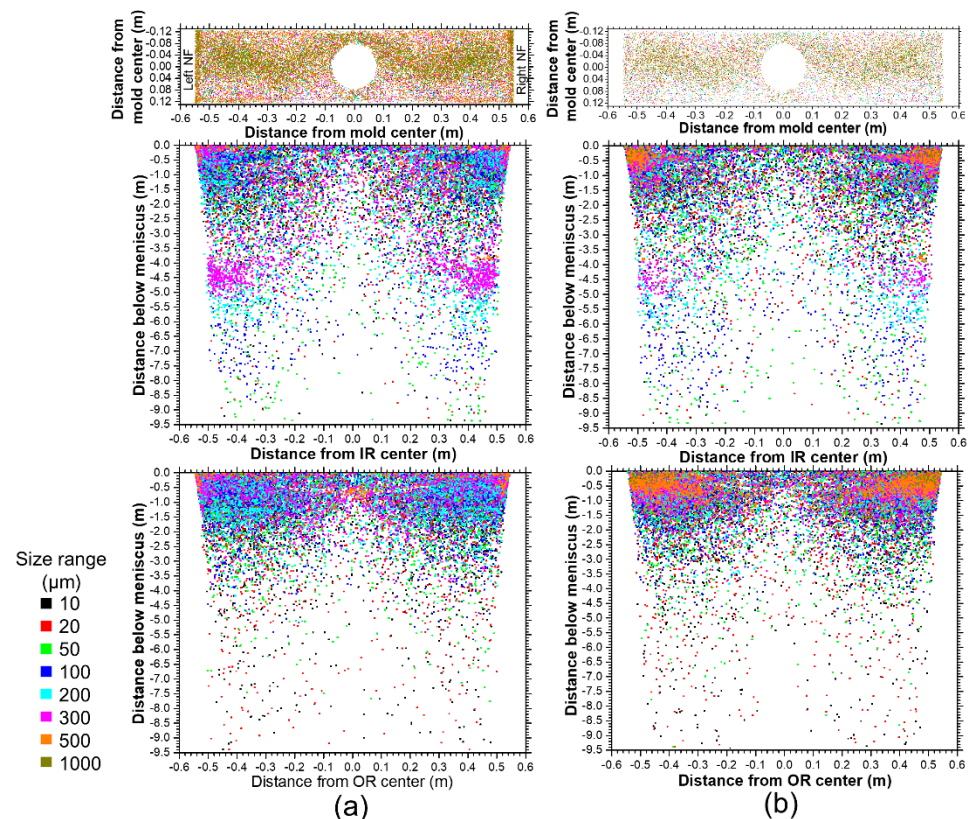


Figure 11. Inclusion capture locations on top surface slag layer (top view, upper frame), IR steel shell (front view middle frame), and OR steel shell (front view lower frame), comparing (a) advanced capture criterion and (b) simple capture criterion predictions.

4.3. Model Validation with Plant Measurements of Captured Inclusions

The locations of captured particles measured from the UT measurements are shown in Figure 12. Here, LNF and RNF are left narrow face and right narrow face, respectively. These measurements clearly reveal a band of particle capture accumulation near the WF IR (red arrow). The location and magnitude of this band matches the capture accumulation band of large inclusions (200 to 300 μm diameter) predicted using the advanced particle-capture criterion shown in Figures 7 and 10.

To make a quantitative comparison, the simulated histograms of inclusion capture (Figure 10) are postprocessed using Equation (12), to predict the capture rate in the real steel slab sample. First, the calculated effective injection times for each inclusion size, $t_{pre,i}$ are given in Figure 13a. The corresponding time scale factor for each inclusion size, S_i is given in Figure 13b. This factor is the ratio of the casting time that the measurement sample length spends in the caster exposed to particle capture, t_{mea} , and $t_{pre,i}$. Casting the 103 mm long sample at 26.7 mm/s, the measurement time, t_{mea} , represents 4 s of exposure. Thus, S_i represents the ratio of actual capture in the measured sample with the simulated capture, for each inclusion size ($S_i = R_{c,i} / N_{c,i} = t_{mea} / t_{pre,i}$). Figure 13b shows that in order to achieve good statistics, the model simulates many more large particles and many fewer small particles, compared to the steady-state operation in the real plant. Thus, the new postprocessing methodology saves greatly on computation. The redrawn histograms showing the actual capture rates predicted in the steel slab sample are given in Figure 14. These histograms can be compared directly with the UT measurements of the number of large particles captured in the steel slab sample during its 4s of measurement time.

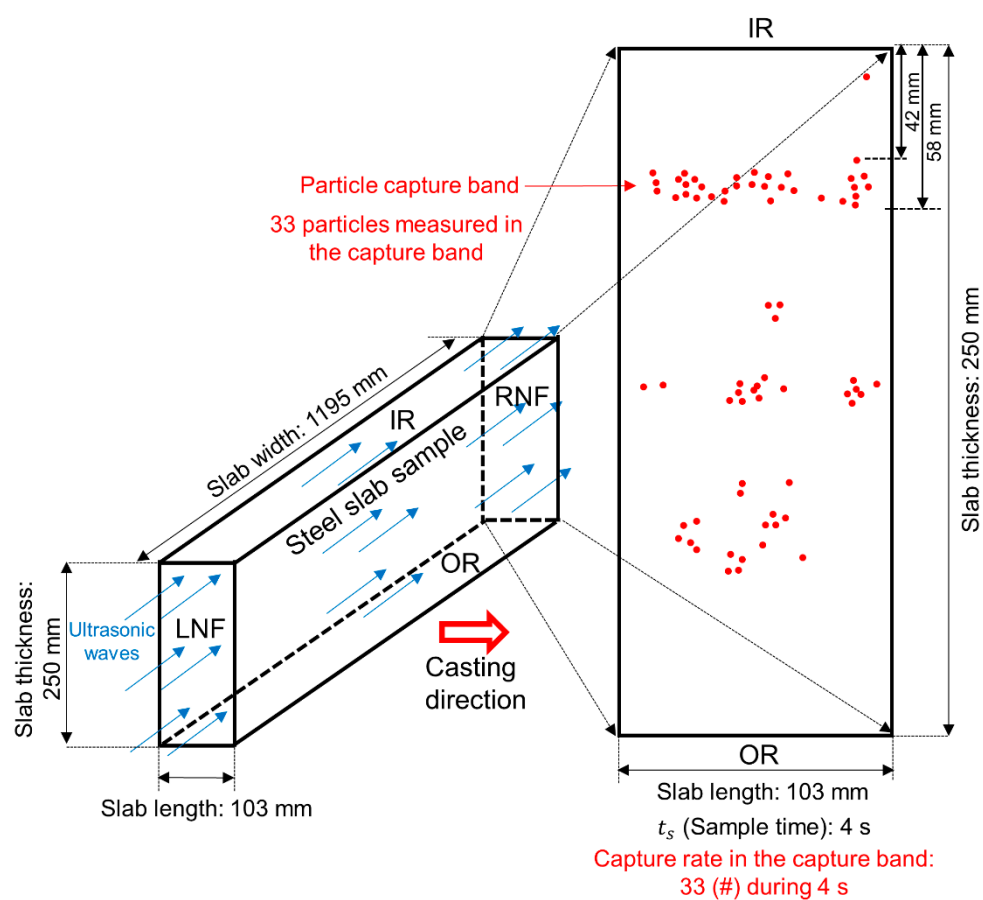


Figure 12. Particle capture locations in the steel slab sample, based on UT measurements (side view).

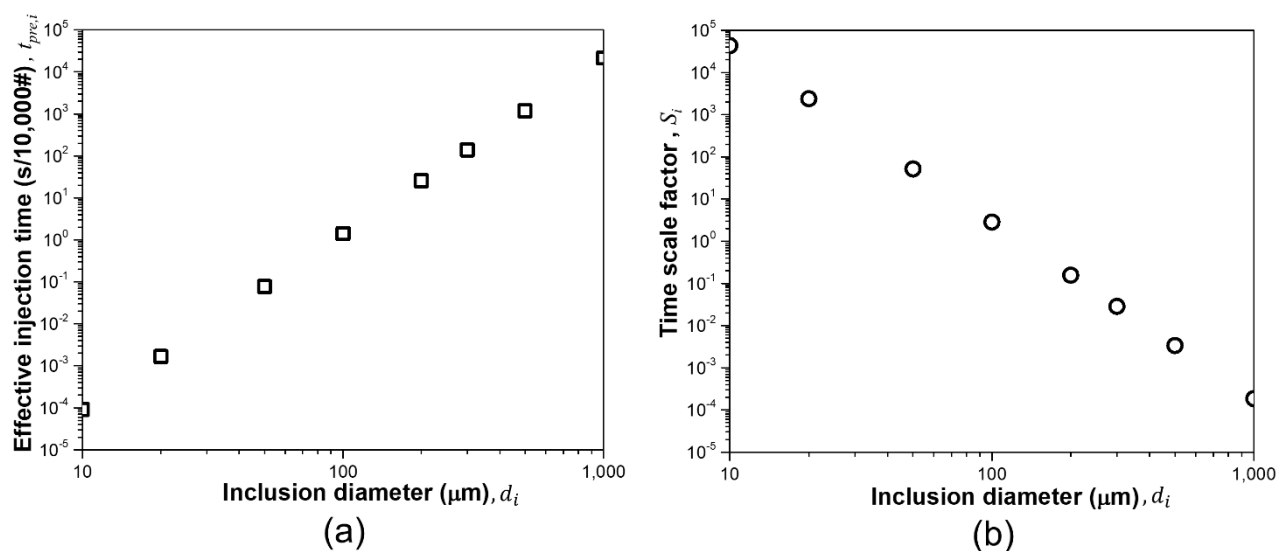


Figure 13. (a) Effective injection time (per 10,000 particles of each size), $t_{pre,i}$ and (b) time scale factor, S_i , by inclusion size.

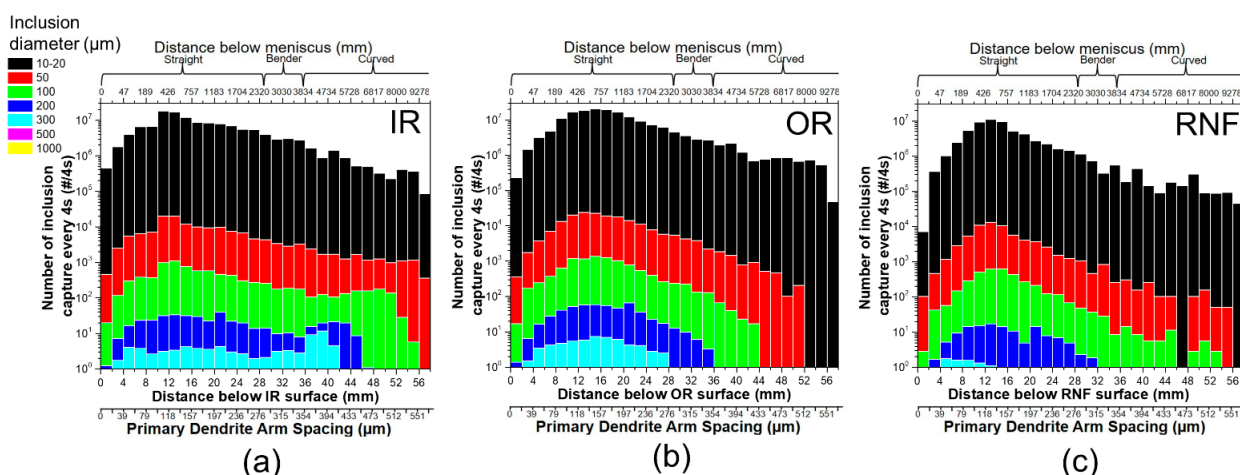


Figure 14. Histograms of the predicted inclusion capture rate in the steel sample, by locations and sizes of the captured inclusions: (a) the IR shell, (b) the OR shell, and (c) the right NF shell.

Figure 15 shows the measured capture rate of large inclusions ($\geq 300 \mu\text{m}$) in the capture-band region of the as-cast slab sample. The horizontal solid-green line, Method 1, is the average of the model capture rates in this region from Figure 14a post-processed with Equation (12). The horizontal dashed-black line, Method 2, is the time-average of the instantaneous capture rates plotted in the histogram. The Method 2 calculation is based on 60 s of modeling time taken when the particle capture rate was in steady-state, and enables an evaluation of the standard deviation of the capture rates. The horizontal dashed-red line is the UT measurement. Both the predictions and the UT measurements show a capture rate of $\sim 30 \text{ #/4 s}$ of inclusions larger than $300 \mu\text{m}$ in the capture accumulation region. The measured number of captured inclusions falls within the standard deviation of the model prediction. This indicates that the advanced particle capture criterion with the new postprocessing methodology on capture model results is able to quantitatively predict inclusion capture defects. Furthermore, the model provides new insight into the capture mechanism of this band of inclusion defects, which often forms in continuous casting of steel slabs with a straight mold and vertical segment, followed by bending and a curved lower strand.

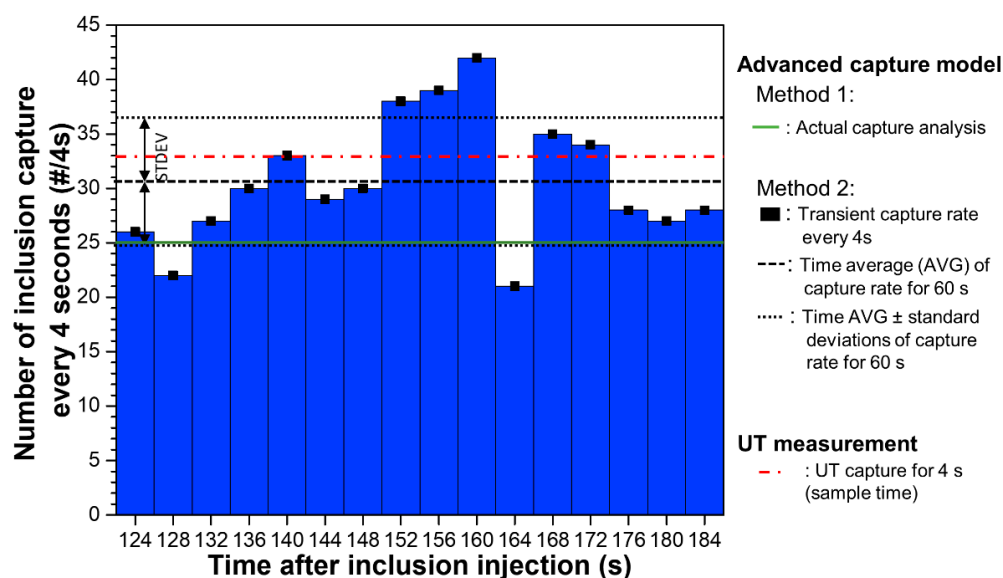


Figure 15. Capture rate of large inclusions ($\geq 300 \mu\text{m}$) in the capture band of the steel sample, comparing the particle capture modeling (histogram and black line) with the UT measurements (horizontal red line).

4.4. Inclusion Capture Fractions

Based on the results from the validated model simulations of the locations of captured inclusions, a map of the fractions of inclusions captured in different regions of the strand is given in Figure 16. Many inclusion particles (~32%) float to the top surface and are removed by the mold slag. Most particles are entrapped by the solidifying steel shell in the mold and vertical portion of the upper strand (~56%), where the transport and capture of particles depends strongly on the jet behavior and flow pattern. Fewer inclusions are captured in the short bender region (~4%). Very few inclusions are captured lower in the long, curved part of the strand (~4%), including capture in the accumulation band on the IR wide face, in the short region (4–6 m below meniscus) at the beginning of the curved part of the lower strand, as discussed in Sections 4.2 and 4.3. Although few in number, these inclusions are important due to their large average size. Finally, very few particles (~4%) penetrate deep into the strand, past the bottom of the model domain at 9 m below the meniscus, where they are expected to be captured as internal defects.

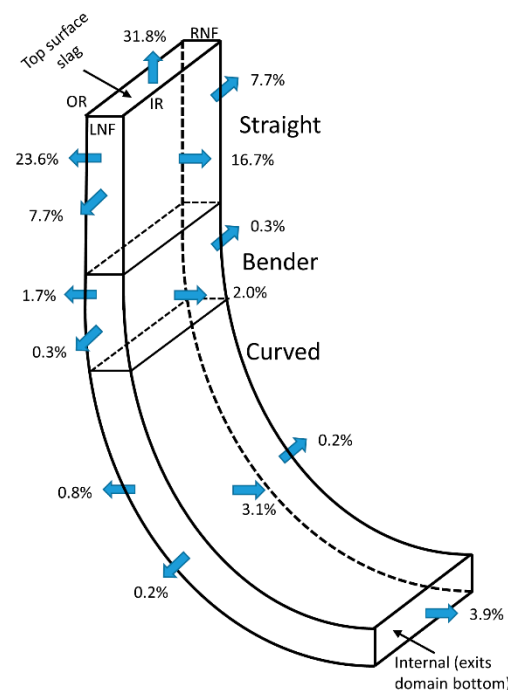


Figure 16. Fractions of inclusions captured in different strand regions.

Figure 17 provides details of the capture percentages of inclusions according to inclusion size. The rest of the inclusions are removed into the surface slag layer, and this removal fraction is shown as well. Small inclusions ($\leq 100 \mu\text{m}$ diameter), have a high (>90%) capture percentage, as they follow the flow pattern. Large particles ($\geq 1000 \mu\text{m}$) are almost all removed, owing to their high buoyancy. Intermediate-sized inclusions (200 to 500 μm diameter) show a large slope of the removal/capture fraction lines, indicating that capture is very sensitive to inclusion size and flow conditions for this critical size range. The removal percentage of these inclusions increases greatly with inclusion size. Within this critical size range, 60–80% of inclusions with diameters of 200 μm to 300 μm are captured into the steel shell and show an accumulation band near the beginning of the curved part of the strand, 4–6 m below the meniscus.

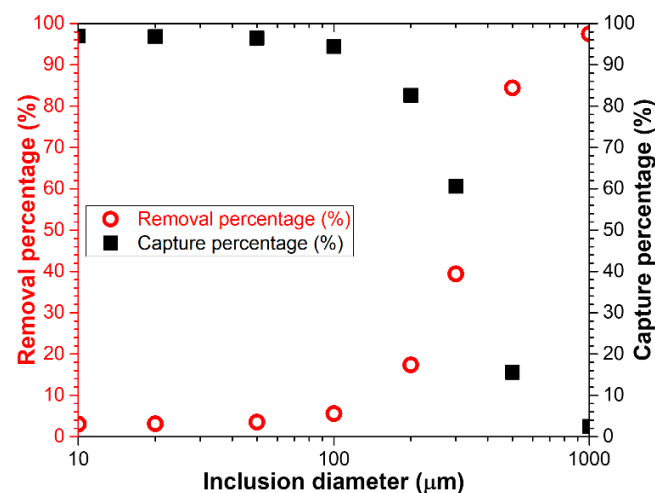


Figure 17. Removal percentage and capture percentage by inclusion size.

4.5. Inclusion Capture Mechanisms

Mechanisms of the inclusion capture into the steel shell are evident from the results of this investigation. To understand the mechanism of the large inclusion capture accumulation at 4–6 m below the meniscus, the terminal ascending velocity of the inclusions can be calculated using Equation (13), which arises from the force balance calculated as part of the DPM model, when the drag force and the buoyancy/gravity forces acting on each inclusion are in balance:

$$u_{p,terminal} = \sqrt{\frac{4}{3} \frac{\rho - \rho_p}{\rho} \frac{d}{C_D} g} \quad (13)$$

where ρ is the density of molten steel (7020 kg/m³), ρ_p is the density of the inclusions (2800 kg/m³), d is the inclusion diameter, C_D is drag coefficient [29], and g is gravitational acceleration (9.81 m/s²).

Large inclusions with diameters of 200, 300, and 500 μm have terminal ascending velocities in the range of 0.01–0.04 m/s. These upward velocities of the inclusions are compared in Figure 18 with the model simulation of downward velocity profiles of the molten steel (Lines 1–5: defined in Figure 5c) in the capture accumulation region (4–6 m below the meniscus). The molten steel velocity profiles are asymmetric with the highest velocity ~0.038 m/s found between the WFs. Velocity is slightly slower towards the IR steel shell front, where it roughly matches with the terminal ascending velocity ($u_{p,terminal}$: 0.01–0.02 m/s) of the 200–300 μm large particles. These matching velocities enable these large inclusions to become suspended at the IR solidification front, where they are more easily captured. This may help to explain the capture accumulation band in this region.

More importantly, the steel solidification front has PDAS growing to 360–440 μm in the accumulation region, as shown in Figure 3, which is larger than the inclusions (200–300 μm). Thus, these inclusions can fit between the dendrites in this region to become entrapped. This is a second phenomenon to explain the capture accumulation band at the beginning of the curved part of the strand, observed in the real steel sample.

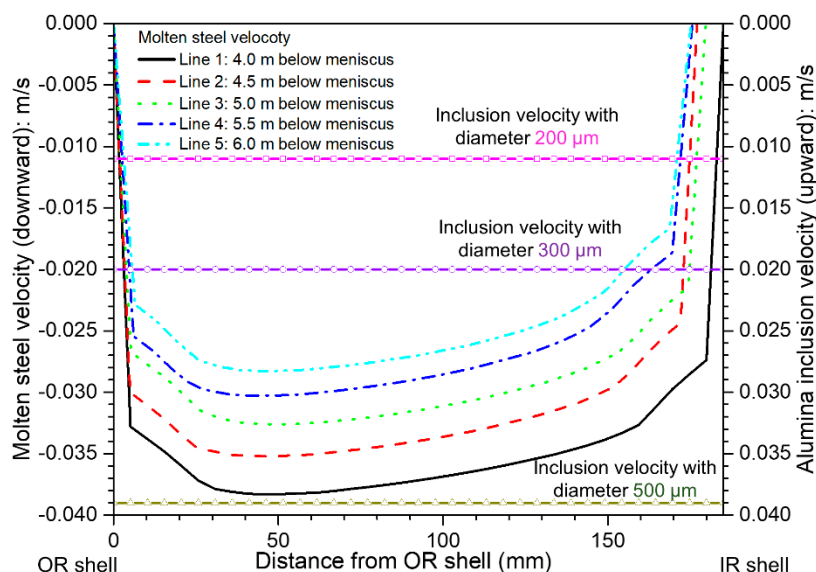


Figure 18. Comparison of molten steel velocity profiles through the strand thickness at the w/8 plane in the strand region 4–6 m below the meniscus with the terminal ascending velocity of three large inclusion sizes.

Figure 19 compares the two mechanisms of inclusion capture by inclusion size. Most of the small size inclusions ($\leq 100 \mu\text{m}$) captured into the steel shell are due to the entrapment between the PDAS. On the other hand, most ($\geq 80\%$) of the captured large particles ($\geq 300 \mu\text{m}$) are captured by engulfment: the inclusions balance at the steel shell front, and then become surrounded by the growing dendrites. Inclusions in the capture band were mainly 200–300 μm and were captured almost entirely by entrapment. This shows that PDAS is very important for the capture of large inclusions deep into the strand region, as well as the local steel flow velocity across the solidification which controls the drag, and the other forces which push the inclusions towards the steel shell front and thereby lessen the chance of rotation.

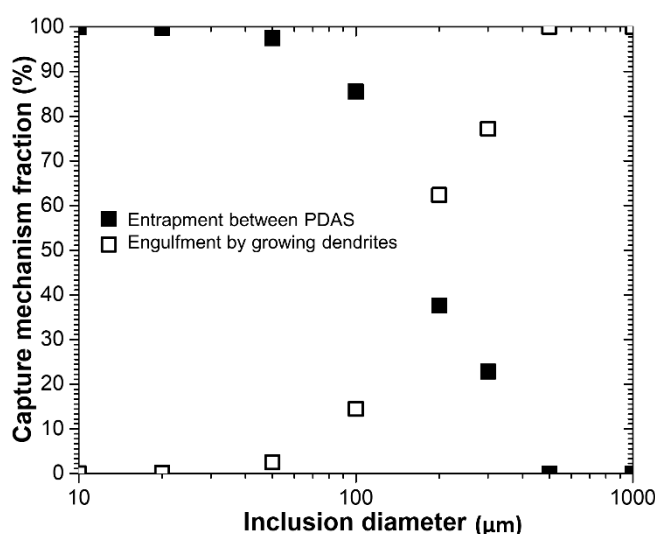


Figure 19. Inclusion capture mechanisms by inclusion size.

Even though very few large inclusions are captured, as indicated by their small capture fractions in Figure 17, they are very detrimental to the quality of cast steel products,

as indicated by the capture band observed in the steel slab sample. Captured internal inclusions cannot be removed during subsequent processes, such as annealing and rolling. Thus, this new understanding of capture mechanisms of large particles is important to enable practical strategies to lessen them. Specifically, strategies to avoid engulfment of large inclusions is to produce desirable flow patterns which wash across the solidification front, such as aided by electromagnetic stirring, control of the nozzle port geometry to produce jets that minimize velocity down the narrow faces which takes large inclusions deep into the caster, and the avoidance of large, slow, recirculation regions such as form near the transition from vertical to curved parts of the strand, such as by applying strand EMS [43–45].

4.6. Future Work

The particle capture modeling and postprocessing methodology presented here, validated with plant measurements, show promise for the quantitative calculation of particle capture in commercial continuous casting of steel. With its reasonable computational efficiency, this methodology enables parametric studies of particle capture for various process conditions, which is needed to find optimal process conditions to minimize particle capture defects in continuous casting processes.

To improve the accuracy of particle capture calculations, further work is needed to quantify the inclusion size distributions entering the mold and strand, based on measurements and modeling of inclusion behavior in the upstream processes including steelmaking, ladle, tundish [32], and transfer operations. In addition, the modeling of other mechanisms of inclusion formation and capture in the caster should be improved. Subsurface particle capture beneath meniscus hooks at oscillation marks is often observed, especially in casting of ultra-low carbon steel grades, and with slow surface velocities [46,47]. This can be incorporated with a hook capture model, such as presented in [30]. In addition, particles reaching the liquid mold flux/molten steel interface on the mold top surface are not always immediately removed, so more complex phenomena related to surface tension effects on particle removal should be modeled. Likewise, more realistic surface-slag layer capture models are needed to calculate mold slag entrainment, which involves many different submechanisms [3]. Also, modeling of the interaction between argon bubbles and inclusions [48] and inclusion agglomeration is important. Finally, the flow of small inclusions between dendrite arms should be considered for more accurate removal and capture at the solidification front. Together with the advanced capture criterion, such model advances should enable even more realistic prediction of inclusion capture, and the design of plant practices to lessen inclusion capture.

5. Conclusions

Inclusion capture in a steel slab caster with a vertical mold and top section followed by bending and a curved lower strand is quantified by applying a three-dimensional computational model of turbulent molten-steel flow using a RANS-based standard k - ϵ model, the transport of inclusions using a Discrete Phase Model (DPM), and the capture of inclusions using an advanced capture criterion. The model predictions are validated with Ultrasonic Testing (UT) measurements of the locations of large particles captured in a sample of a continuous-cast steel slab from a commercial steel plant. Important findings include:

- The advanced capture criterion including particle capture mechanisms due to both 1) entrapment between Primary Dendrite Arm Spacing (PDAS) and 2) engulfment by growing dendrites, is capable of accurately predicting the locations and size distributions of inclusion particles captured into the steel shell during continuous casting, including the important capture of large inclusions deep into the strand.
- A new methodology of postprocessing the predicted particle capture results has been developed to enable quantitative, accurate calculation of actual capture rates in the

steel slab, based on statistically-reliable numbers of inclusions with reasonable computational burden.

- The straight-curved strand casting of steel slabs produces a classic double-roll flow pattern with a maximum surface velocity (~ 0.2 m/s) almost within the safe operation window, and strong flow (~ 0.3 m/s) down the narrow faces in the mold region.
- An accumulation band is observed near the inside radius of steel slabs cast in these straight-curved strand casting machines. This capture band consists mainly of large inclusions ($200\text{--}300\text{ }\mu\text{m}$) with a capture rate of ~ 30 #/4s. This band arises 4–6 m below the meniscus, at the beginning of the curved part of the strand.
- The capture band coincides with a local decrease in flow velocity (<0.02 m/s) near the solidification front due to lower velocity flow along the IR WF in the strand thickness/length plane caused by the transition in the strand geometry (curvature).
- The model with the advanced capture criterion simulation accurately predicts both the location and number of inclusions captured in the accumulation band near the beginning of the IR curved part of the strand.
- The capture band is caused partly by the low molten steel velocity in this region (downward) almost matching the inclusion rising terminal velocity (upward), which suspends large inclusions ($200\text{--}300\text{ }\mu\text{m}$) at the steel shell front on the IR WF, and makes particle capture easier. The second, more important reason is that the increasing PDAS down the caster begins to exceed the size of the larger inclusions in this region, enabling easier entrapment between dendrite arms.
- The relative importance of different inclusion capture mechanisms is revealed: small inclusions are mainly captured by entrapment between dendrites, while large inclusions are captured mainly by engulfment, by being surrounded by growing dendrites while being almost suspended near the solidification front in low-velocity regions of the flow pattern.
- The engulfment mechanism (advanced capture criterion) explains the capture of inclusions larger than the local PDAS and suggests ways to prevent this phenomenon.
- Lessening the capture of large inclusions entering the mold can be accomplished by comprehensive control of the molten steel flow by optimizing both nozzle and strand geometry and careful application of electromagnetic stirring, in order to direct particles towards the top surface without excessive surface velocity, to avoid strong flow down the narrow faces, and to wash particles away from the solidification front by avoiding low velocity regions.
- Future work is needed to implement further mechanisms of inclusion formation, capture, and removal into the model methodology presented here, and to conduct parametric studies to find practical ways to lessen particle capture in continuous casting.

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