

Simulation and validation of two-phase turbulent flow and particle transport in continuous casting of steel slabs

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Abstract. In continuous steel casting, argon gas is usually injected at the slide gate or stopper rod to prevent clogging, but entrapped bubbles may cause defects in the final product. To better understand this, the flow of molten steel and the transport and capture of argon gas bubbles have been simulated and compared with plant measurements. First, the flow field was solved with an Eulerian k- ϵ model of the steel, which was two-way coupled with a Lagrangian model of the large bubbles using a Discrete Random Walk method to include dispersion of bubbles due to turbulence. The asymmetrical flow pattern predicted on the top surface agreed well with nailboard measurements. Then, the motion and capture of over two million bubbles were simulated using two different capture criteria. Results with the advanced capture criterion agreed well with measurements of the number, locations, and sizes of captured bubbles, especially for larger bubbles. The relative capture fraction of 0.3% was close to the measured 0.2% for 1mm bubbles, and occurred very near the top surface. The model presented here is an efficient tool to study the capture of bubbles and inclusion particles in solidification processes.

1. Introduction

Argon bubbles captured during the continuous casting of steel are a major cause of defects, such as blisters and slivers, in rolled steel products. During the casting process, Ar gas is usually injected at the slide gate or stopper rod. The jet of molten steel then carries those Ar bubbles pass through the Submergence Entry Nozzle (SEN) and into the mold cavity. During this transport, the bubbles may pick up inclusions, thereby forming inclusion clusters which lower the steel quality if captured [1, 2]. Bubbles entering the mold region have 3 possible fates: (1) some reach the top surface, pass through the slag layer and escape harmlessly to the atmosphere; (2) some are captured near the meniscus and lead to surface defects; (3) some are captured deep in the caster and cause internal defects.

Argon bubbles also affect the flow pattern, including surface level fluctuations, slag entrainment, particle trajectories, and other phenomena important to steel quality. Previous models of two-phase Ar and steel flow in continuous casting [2–6] have used different methods to achieve the necessary two-way coupling to predict the flow pattern, and reveal the importance of the larger bubbles.

Relatively few studies [2–4] have investigated quantitatively the capture rate and distribution of inclusion particles in continuous casting. Yuan, Thomas and Vanka [3] performed particle capture simulations for small bubbles (less than 40 μm) in a thin-slab steel caster using Large Eddy Simulation (LES) where the effect of transient local turbulent eddies on particle transport was automatically included. A removal rate of 8% of small inclusions was predicted, independent of both particle size and density, which suggests that their particles were too small to deviate significantly from the surrounding fluid flow. Zhang and Wang [5] performed 3D one-way coupled $k-\varepsilon$ simulations, adding sink terms at the solidification front to model the momentum loss due to solidification, and a random-walk method [7, 8] to include turbulent dispersion of small (5 μm) particles [3] in a simulation of a full-length billet caster. Capture was assumed when particles touched the solidification front, defined by a solid fraction of 30% or 60%. This capture criterion may be reasonable for particles smaller than the PDAS [2–4].

To properly predict the capture rate and location of different Ar bubbles/particles, a suitable capture criterion is needed. Yuan and Thomas [2, 3] developed a particle capture criterion based on a local force balance on particles reaching the solidification front. This model includes the effects of particle size, Primary Dendrite Spacing (PDAS), concentration gradient forces and other effects. This capture criterion was successfully validated with previous measurements, so is used in the current study. Further work with this criterion [2–4] has investigated the entrapment of slag inclusions, alumina clusters, and bubbles during continuous slab casting. They found that to more accurately predict the removal rate of particles (error within $\pm 3\%$), more than 2500 particles should be injected into the domain. The work presented here investigates different capture criteria (“simple” and the previous criterion [2, 3]) for predicting Ar bubbles with different diameters in a real commercial continuous caster.

2. Plant measurements

Plant measurements of fluid flow and bubble entrapment were conducted on the No. 4 caster, which is a conventional (230 $\times$ 1300 mm) continuous steel slab caster, at Baosteel Shanghai in 2012. Top surface velocities were measured with two sets of nailboard dipping tests, which are widely used to measure mold surface flow [4]. Casting conditions and process parameters are given in table 1. Flow rate of the molten steel through the SEN into the mold is controlled by a slide-gate that moved between the geometric center and the Inside Radius (IR) side of the caster. The slide gate was 70% open at 1.5 m/min, as shown in figure 1.

Table 1. Process parameters

Process Parameters	Value
Mold thickness (L_t)	230 mm
Mold width (L_w)	1300 mm
Casting speed (V_c)	1.5 m/min
Argon volume fraction (α)	8.2 vol%
Steel density (ρ)	7000 kg/m ³
Argon density (ρ_p)	0.5 kg/m ³
Steel viscosity (μ)	6.30 $\times 10^{-3}$ kg/(m·s)
Ar viscosity (μ_p)	2.12 $\times 10^{-5}$ kg/(m·s)
Sample length in casting direction (Δz)	150 mm

Argon gas was injected in the slide gate region to prevent reoxidization and clogging. To evaluate the capture of Ar bubbles during the solidification process, 150 $\times$ 150 mm² samples were cut from the center and quarter of the Wide Face (WF), and Narrow Face (NF) of the final steel slab, as shown in figure 2. The outer 3 mm of the surface of each sample was milled away (NF or WF), and a 35X optical microscope was used to count the number of bubbles on that surface and their diameters.

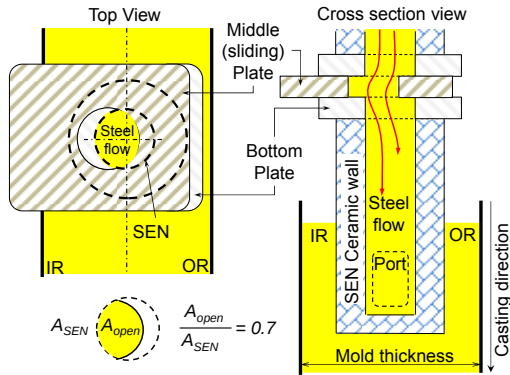


Figure 1. Slide gate configuration

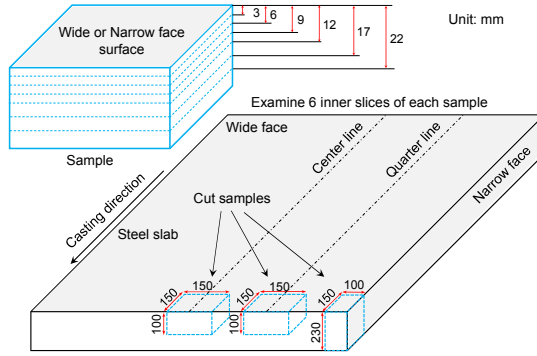


Figure 2. Samples and six examined surfaces

After recording the results, another 3 mm of steel was milled away and the new exposed surface was measured in the same way. This procedure was repeated to examine six layers, located at 3, 6, 9, 12, 17 and 22 mm beneath the outer surface. The symbol s_j is used to represent the distance beneath the outer surface (NF/WF), $s_1 = 3$ mm, $s_2 = 6$ mm, and etc.

3. Computational models and solution procedure

A three-dimensional finite-volume computational model together with Lagrangian particle tracking was applied to study the flow behavior and the transport phenomena of Ar bubbles in a commercial continuous steel caster. First, a steady-state solution of single-phase flow of molten steel was obtained using standard $k-\epsilon$ model. Then, based on that solution, a RANS and Lagrangian Discrete Phase Model (DPM) coupled simulation was used to predict pseudo steady flow, including the effect of Ar gas. The Discrete Random Walk (DRW) model was used to include the effect of turbulence on bubble dispersion. The gas buoyancy affects only the liquid momentum equation, which is a valid approach when gas volume fraction is low ($\sim 12\%$). Based on this flow field, many bubbles were injected at the SEN inlet to study the transport and capture of Ar bubbles. Two different capture models were implemented into ANSYS FLUENT [7] using User Defined Functions (UDFs) and the results were compared.

3.1. Bubble size distribution model

In this work, the total volume of the hot Ar gas V_g was divided into eleven different bubble size groups according to the Rosin-Rammler [9] distribution originally used to describe solid particle distributions, as given in figure 3 and equation (1). The black dashed line is the ideal Rosin-Rammler cumulative distribution F for a mean diameter $\bar{d} = 3$ mm and spread parameter $\eta = 4$.

$$F(d_i) = \frac{V_{g(d < d_i)}}{V_g} = 1 - \exp\left(-\frac{d_i}{\bar{d}}\right)^\eta \quad (1)$$

The blue squares represent the diameter and volume fraction of each group of bubbles of the total Ar volume. The red staircase line is the summation over the volume fraction of bubbles with diameter less than the specified diameter. Note that the Rosin-Rammler distribution passes through the cumulative line of the discrete points. Note also that less than 1% of the bubbles have diameter less than 1 mm.

3.2. Two-way coupled steel-Ar flow model

The computation domain contains half of the slide-gate, SEN and mold region (from meniscus surface to 2.5 m below meniscus). The mesh contained ~ 1 million hexahedral finite volume cells as shown in figure 4. A single-phase steel flow simulation was first carried out with the $k-\epsilon$ model to provide an initial guess for the later two-way coupled steel-Ar flow simulation.

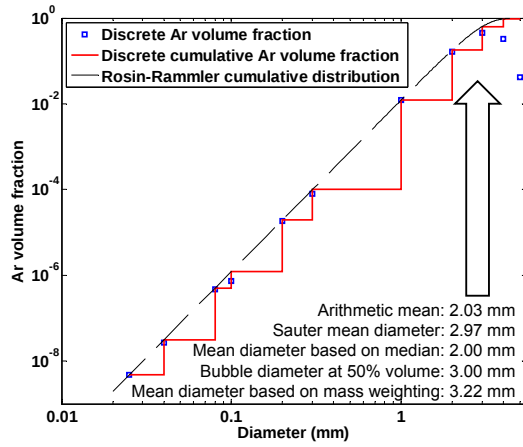


Figure 3. Ar bubbles mean diameters and volume fraction distribution.

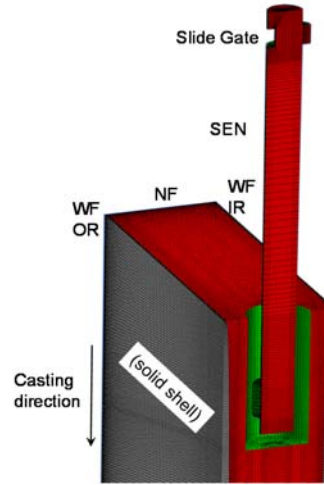


Figure 4. Mesh of the computational domain (Slide gate, SEN and mold)

The solid shell is included in this domain and the shell thickness was determined by $s(mm) = 3\sqrt{t(s)}$. The solid shell (necessary for later study of magnetic field effects) is modeled as a solid zone where the fluid flow equations are not solved. The continuity and momentum equations for liquid steel are:

$$\nabla \cdot (\rho \vec{U}) = S_{\text{mass-sink}} \quad (2)$$

$$\rho \frac{\partial \vec{U}}{\partial t} + \rho (\vec{U} \cdot \nabla) \vec{U} = -\nabla \left(\bar{p} + \frac{2}{3} \rho k \right) + \nabla \cdot [(\mu + \mu_t) \nabla \vec{U}] + \vec{S}_{\text{momentum-sink}} + \vec{S}_{\text{DPM}} \quad (3)$$

The source term from the DPM model $\vec{S}_{\text{DPM}}$ was included in equation (3) in the two-way coupled simulation step to include the drag of each rising bubble acting on the local fluid [7]. Mass and momentum sinks were added near the shell through UDFs to include the effect of the solidifying shell, as explained elsewhere [4]. The k - ϵ model was used to model turbulence [10].

At the slide gate inlet, fixed uniform velocity inlet boundary conditions $V_{\text{inlet}} = 1.69$ m/s were applied based on the steel flow rate (0.007475 m³/s) divided by inlet area (0.0044 m²). The turbulent kinetic energy and its dissipation rate were assumed to be small as 10⁻⁴ m²/s² and 10⁻⁵ m²/s³. A pressure outlet boundary condition was applied at the domain bottom to include the ferrostatic pressure of the steel (171.5 kPa) based on the distance (2.5 m) below the top surface multiplied by the density and gravity constant. The turbulent kinetic energy and dissipation rate were specified as 10⁻⁵ m²/s² and 10⁻⁵ m²/s³ for reverse flow from the bottom boundary, respectively. A free slip boundary condition was applied at the top surface. The WF and NF solidification fronts and SEN walls were no slip and no penetration walls.

After the single-phase fluid flow solution was obtained, the Lagrangian DPM tracking and DRW models were used to include the effect of the Ar bubbles on steel flow to correct the flow pattern. The following force balance equation was solved for each individual bubble, of volume V_p .

$$\rho_p V_p \frac{d\vec{u}_p}{dt} = \underbrace{\frac{18\mu C_D}{d_p^2} V_p (\vec{u} - \vec{u}_p)}_{\vec{F}_D} \underbrace{\left(\frac{\rho d_p |\vec{u}_p - \vec{u}|}{\mu} \right)^{\text{Re}_p}}_{\vec{F}_v} + \underbrace{0.5 \rho V_p \left(\frac{D\vec{u}}{Dt} - \frac{d\vec{u}_p}{dt} \right)}_{\vec{F}_p} + \underbrace{\rho V_p \frac{D\vec{u}}{Dt}}_{\vec{F}_p} + \underbrace{\vec{g} V_p (\rho_p - \rho)}_{\vec{F}_b} \quad (4)$$

where the four forces are: drag $\vec{F}_D$, virtual mass $\vec{F}_v$, pressure gradient effect $\vec{F}_p$ and buoyancy/gravity $\vec{F}_b$. The drag force depends on particle Reynolds number Re_p and drag coefficient C_D from Morsi [11].

The first 3 of these forces comprise $\bar{S}_{\text{DPM}}$. To save computation time and considering that Ar bubbles < 1 mm comprise <1% of the gas, only large bubbles (1 – 5 mm) were injected and tracked in this two-way coupled calculation. The effect of turbulence on particle dispersion was modeled using the DRW method, where the local fluid velocity $\bar{u}$ is written as $u_i = U_i + u'_i$ where U_i is mean velocity obtained from the RANS model, and u'_i is a Gaussian distributed random velocity fluctuations generated using $u'_i = \zeta \sqrt{u_i'^2} = \zeta \sqrt{2k/3}$, where ζ is a random number from a standard normal distribution. The value of ζ was changed to produce new u'_i when the smaller of the eddy lifetime t_e (time scale of an eddy) and eddy crossing time t_{cross} (time for particle to cross an eddy) was reached.

3.3. Argon bubble tracking and capture models

After calculating the pseudo steady state two-phase flow solution, ~2.5 million particles were injected into the domain and their trajectories were tracked. The number of bubbles injected with diameter d_i , denoted $N(d_i)$, is determined according to match the plant experiment conditions as follows:

$$N(d_i) = \frac{3\alpha_i}{4\pi(0.5d_i)^3} \cdot \alpha \frac{\Delta z L_t (0.5L_w)}{1 - \alpha} \quad \text{where} \quad \alpha_i = \begin{cases} F(d_i) & i = 1 \\ F(d_i) - F(d_{i-1}) & i > 1 \end{cases} \quad (5)$$

where V_g is the hot Ar gas volume injected into half of the caster during the time to cast the 150 mm length sample. L_t and L_w are the thickness and width of the mold, respectively. Δz is the sample length which equals 150 mm in this study. α is the total Ar volume fraction which is 8.2%. The volume fractions of bubbles with different sizes are denoted as α_i , and can be determined based on $F(d_i)$ from equation (1). Following these equations, 244,239 bubbles were injected. To make the results statistically more reliable, this bubble tracking calculation was repeated 10 times, meaning ~2.5 million bubbles were tracked for each capture criterion case.

Two different capture criteria were investigated in this work: (1) a “simple” capture criterion which assumes immediate capture when a bubble/particle touches the solidification front; (2) an “advanced” capture criterion, based on the force balance proposed by Yuan and Thomas [2, 4]. For small bubbles less than the PDAS, the particle can enter between the dendrite arms and be captured by entrapment. For bubbles/particles greater than the PDAS, the advanced criterion considers 8 forces acting on a spherical bubble/particle touching three dendrite arms, shown in figure (5). The bubble is suspended and then captured if the tangential drag forces from the flowing fluid that try to rotate it are insufficient to overcome a force balance with the other forces acting on the particle. These forces include those in equation (4), and also the lift force, lubrication force, Van der Waals force, and surface tension gradient force. Details on these forces and this advanced criterion can be found in previous work [2, 4].

3.4. Plant-sample evaluation model

To compare with plant measurements, the bubbles expected to be observed on each sample surface must be extracted from the simulation data. A captured bubble k with radius r_k and captured a distance beneath outer surface h_k , can be observed on sample surface j located distance s_j beneath the outer slab surface (WF/NF) only if it satisfies one of the following conditions:

$$\{h_k < s_j \text{ and } h_k + r_k > s_j\} \text{ or } \{h_k > s_j \text{ and } h_k - r_k < s_j\} \quad (6)$$

A post-processing calculation was conducted to check these conditions for each bubble, and to extract the number and average diameter of bubbles observable on each examined sample layer.

The observed diameters then were adjusted to reflect the true bubble size, considering that the examined surface rarely passes through the center of the bubble, so the visible circle is smaller than the true 3D diameter. Specifically, the method proposed by Lekakh et al. [12] was used to convert each visible diameter to its true diameter via $0.785d_{\text{true}} = d_{\text{visible}}$.

4. Model validation

4.1. Top surface velocity

Figure 6 compares the speed across just beneath the top surface centerline from the pseudo steady-state two-way coupled flow results with the plant nailboard measurements. The predicted cross flow from IR toward OR agrees with the plant measurements. This cross flow was not observed in the single-phase flow results. The plant measurements found even stronger cross flow than predicted. However, only two nailboard measurements were available which comprise only 2 snap-shots of the chaotic flow, so perfect quantitative matching is not expected. More accurate transient computations and further measurements would be needed to improve understanding of the steel-Ar flow pattern.

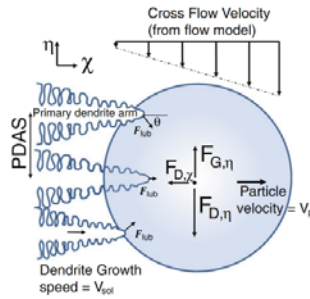


Figure 5. A bubble/particle touching 3 dendrite tips [2]

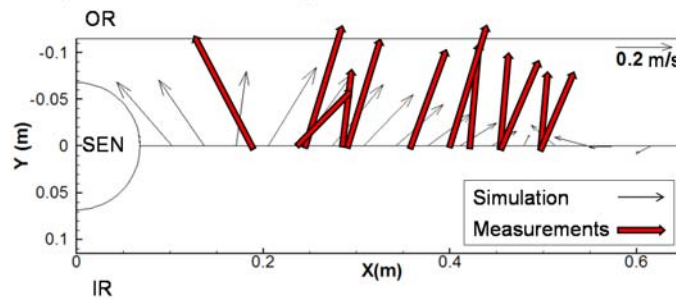


Figure 6. Compare centerline velocity on top surface with plant nailboard measurements

4.2. Capture of small bubbles.

The number and average diameter of bubbles predicted to be captured on the examined sample surfaces are compared with actual measurements in each layer of the plant samples in figure 7. Figures 7(a) and 7(b) show the number of bubbles captured in the central and quarter sample layers, respectively. In the central sample, both criteria under-predicted the number of captured bubbles close to the strand surface. At the quarter region, the advanced capture criterion predicted 20 to 40 bubbles on the first two layers of the examined surfaces, which matches the measurements 35 bubbles. However, the simple criterion over-predicted the number of captured bubbles by 4X, especially in the second layer of the quarter sample. The simple criterion also significantly over predicted the average bubble size, as shown in figures 7(c) and 7(d). The advanced criterion only slightly over-predicted the measured bubble diameters, predicting 0.1 to 0.3 mm, (vs. measured 0.1 to 0.2 mm) in the central sample, and 0.2 to 0.4 mm (vs. measured 0.1 to 0.2 mm) at the quarter sample.

4.3. Capture of large bubbles.

In all of the measured sample layers, ~500 bubbles were observed and only one large bubble (1.4 mm diameter) was observed > 0.5 mm. So, the fraction of all observed captured bubbles that were > 1 mm is $\psi(1 \text{ mm}) = 0.2\%$ (1/500). To predict this capture fraction for > 1 mm bubbles, table 2 shows: the total number of bubbles injected into the domain during the particle tracking step (column 2); the number of 1 mm bubbles injected (column 3); the total number of bubbles captured in the entire caster (column 4); the number of 1 mm bubbles captured in the entire caster (column 5); the fraction of 1 mm bubbles that were captured (column 6), and the fraction of captured bubbles that were larger than 1mm (column 7). These results show that the advanced capture criterion prediction of 0.3% matches very closely to the plant measurement (0.2%). The simple criterion greatly overpredicts the measurements (by 33X).

Table 2. Capture fractions of 1 mm bubbles

Criteria	$\Sigma N(d_i)$	$N(1 \text{ mm})$	$\Sigma n(d_i)$	$n(1 \text{ mm})$	$\phi(1 \text{ mm})$	$\psi(1 \text{ mm})$
Simple	2442390	475640	208944	27799	5.84%	13.3%
Adv.	2442390	475640	137372	432	0.09%	0.3%
Exp.	Unknown	Unknown	~500	1	Unknown	0.2%

5. Results and discussion

The flow pattern calculated in the center plane is shown in figure 8. The standard double-roll flow pattern is modified by the Ar injection. The nozzle jets impinge on the narrow face, and split, sending some recirculating flow upwards and across the top surface towards the SEN. This is met by flow rising up beside the SEN driven by the buoyancy of the Ar gas. Asymmetric swirl caused by the slide gate sends more gas up the inner radius (IR) of the WF, giving complex surface flow with cross flow (figure 6).

Figure 9 shows the capture locations of small bubbles on the WF-IR predicted with the advanced capture criterion, based on the flow field in figure 8. Many 0.3 mm bubbles were captured near the top and SEN side of the caster, with captured bubbles decreasing with distance below the top surface. The horizontal black lines show the location of the examined surfaces in the measurements.

The fraction of each size of bubbles captured is plotted in figure 10. The capture fractions of small bubbles ($d_i < 0.1$ mm) were ~ 0.85 (removal fraction ~ 0.15) for both capture criteria, and were independent of bubble size. This uniformity shows that the capture rate of bubbles smaller the PDAS is governed only by the flow pattern. The capture fraction of large bubbles, on the other hand, decreases dramatically with increasing bubble size. Only 0.1% of 1 mm bubbles are captured with the advanced capture criterion, and no bubble larger than 3mm was captured. The capture fraction drops almost one order of magnitude with increasing bubble size from 1 to 2 mm and from 2 to 3 mm. The removal rate was 99.98% of large bubbles ($1 \leq d_i \leq 5$ mm), 48.5% of medium bubbles ($0.1 \leq d_i \leq 0.3$ mm) and 16.1% of small bubbles ($d_i < 0.1$ mm). Previous RANS and LES studies [2] have shown removal rates of 13% and 47% for 0.1 and 0.4 mm slag particles, which agrees closely with the present results.

6. Conclusions

The flow of molten steel, and the transport and capture of argon gas bubbles have been simulated and compared with plant measurements in a continuous slab caster. A two-way coupled Eulerian-Lagrangian model combined with a bubble tracking DRW model has been applied to predict asymmetrical flow on the top surface, which agrees well with nailboard measurements. Two capture criteria were implemented, and the advanced capture criterion showed good agreement with measurements of the

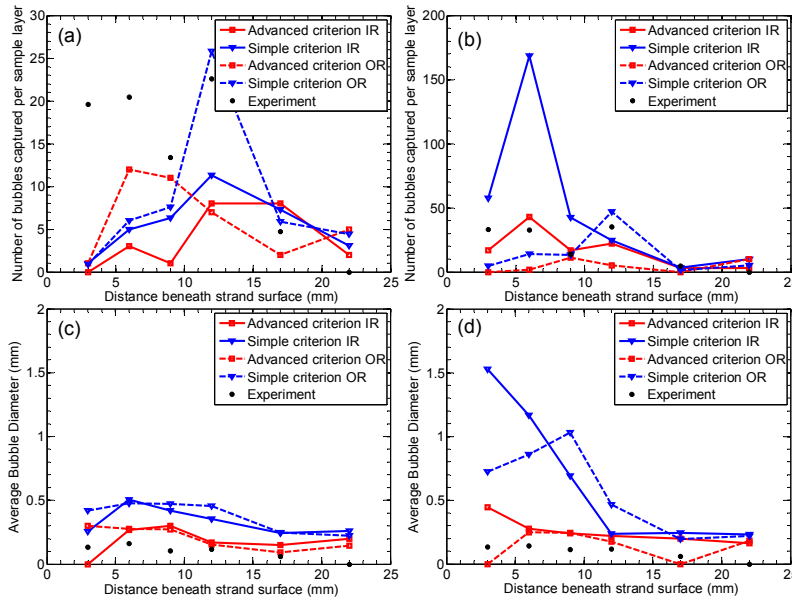


Figure 7. Number of bubbles captured on each sample layer of (a) center and (b) quarter sample; and corresponding average diameter, (c) and (d)

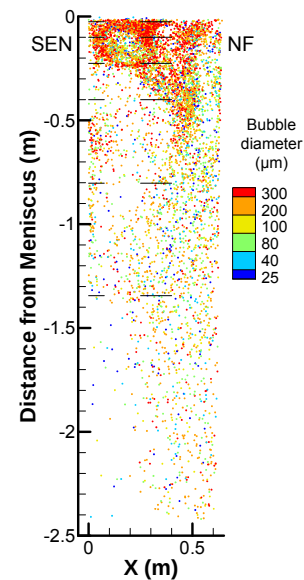


Figure 9. Small bubbles captured on WF-IR with advanced criterion

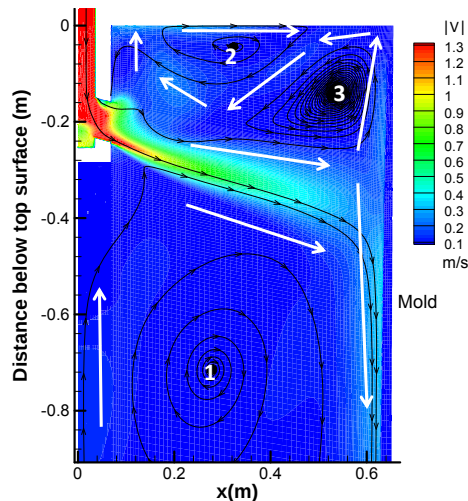


Figure 8. Speed and streamlines in center plane

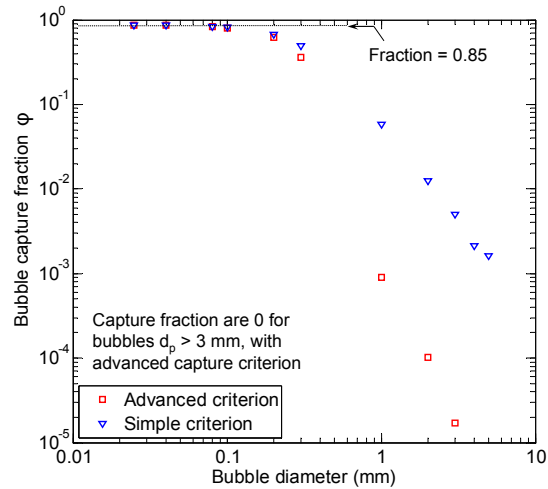


Figure 10. Bubble capture fractions

number, locations, and sizes of captured bubbles, especially for larger bubbles. The capture fraction of 0.3% was close to the measured 0.2% for 1 mm bubbles, and occurred very near the top surface. The model presented here is an efficient tool to study the capture of bubbles and inclusion particles in solidification processes.

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