In-situ Analysis and Numerical Study of Inclusion Distribution in a Vertical-bending Caster

Xianglong LI, Baokuan LI,* Zhongqiu LIU, Ran NIU and Qiang LIU

School of Metallurgy, Northeastern University, Shenyang, 110819 China.

(Received on April 28, 2018; accepted on July 4, 2018; J-STAGE Advance published date: September 4, 2018)

Based on a fast-detection platform (FDP) founded by us, an in-situ measurement of inclusion distribution in slab is successfully performed. The inclusion distribution is obviously asymmetry and non-uniform. Specially, due to the structure differences in the vertical and bending part of a slab caster, the inclusion distribution in these two parts are quite different. In the vertical part, the inclusions entrapped in the outer arc is much more than that in the inner arc, while in the bending part, the inclusions entrapped in the outer arc is a little less than that in the inner arc. Large inclusions are tend to be found near the surface, and sometimes in the center, but they’re very few. Then in order to interpret the inclusion distribution in practical measurements, a new LES model is established using Euler-Lagrange approach. A new entrapment criterion is also defined to calculate the entrapped inclusions. Big inclusions are tend to float up to the mold top, and aggregate near the outer arc, which can explain the differences of inclusion distribution in the vertical part; Smaller inclusions are easier to flow deep into the mold, and become clusters when they’re getting near, which can explain the big inclusions in the central part. What’s more, the drag effect of bending slab is proven to be responsible for the differences of inclusion distribution in the bending part. This mathematical model is helpful for understanding the inclusion movements in slab.

KEY WORDS: Large Eddy Simulation; vertical-bending caster; inclusion entrapment; solidification.

1. Introduction

Inclusion is a big problem during the production of high-performance steels, as they can greatly influence the micro structure and structural properties. They’re often considered as harmful to the final roll product, so that many industrial efforts are contributed to remove inclusions in steel. Another, more positive approach is to use nonmetallic inclusions to produce steels with enhanced or tailored properties. In both cases, the main problem is to control the characteristics of the inclusion population in steel, such as number, composition, morphology, size and spatial distribution. Whether the researcher focuses on theoretical analysis or engineering, modern techniques are essential for the study of this issue. Using metallographic microscope, Warzecha investigated the inclusion size and amounts through different tundish configurations; Using SEM coupled with EMPA, Sengupta showed a high resolution picture of the shapes of bubbles and inclusions near the hook. Recently, based on ASPEX, Ren studied the inclusion morphology changes during different stages of deoxidation. All these works are beneficial for understanding the inclusion distribution in slab, however, due to technical limit, they can only reveal the inclusion distribution in a partial area. Ultrasonic inspection and X-ray detection are more efficient than these methods, and are used to detect the space distribution in slabs, however, the morphology and size are difficult to obtain. Until today, there are still few reports about inclusion morphology, size and space distribution in a whole slab. And the mechanism of inclusion movements is still unclear.

At the same time, many simulations are performed to study the inclusion movements and its entrapment by the shell. Thomas et al. considered normal and tangential force balances involving ten different forces acting on a inclusion in the boundary layer, and the primary dendrite arm spacing (PDAS) was considered for the inclusion entrapment. Liu et al. studied the effect of Magnus and Marangoni force for the behavior of inclusion movements, revealing that the Marangoni force can obviously increase entrapment ratio of inclusions, while Magnus force can reduce the entrapment, especially for the smaller ones. Zhang investigated inclusion removal, slag entrainment, heat transfer, and the breakouts when nozzle clogging. All these works are beneficial for understanding the inclusion movements, however, there is not a unified and precise entrapment criterion, because the entrapment of inclusions at the solidification front is not fully understood.

The CC caster can fall into four categories: vertical type, vertical-bending type, bending type and horizontal type. The vertical caster is the natural machine design, casting with gravity and also assuring a symmetric macro structure, and it is said to be more effective than other casters in removing
bubbles and inclusions. However, the caster productivity is severely limited by machine height, and the cost is expensive. The CC process with the vertical-bending type caster has far fewer internal defect problems than the same process with the curved type caster. So the vertical-bending type caster is the most commonly used in the current CC process. However, even with the vertical-bending caster, defects are still a problem in high quality steel products.

In this work, based on a Fast-Detection platform (FDP) founded by us, an inclusion distribution map was successfully obtained to investigate the inclusion size, morphology and space distribution in a thick slab. The innovations of our paper mainly consist of four parts: (1) to give a detailed inclusion map for the thick slab; (2) to give some special morphologies of macro inclusions in slab; (3) to build a mathematical model as well as a new entrapment criterion for explaining the inclusion distribution in (1); (4) and to find a plausible description of the probability density function (PDF) of inclusions. The results are helpful for understanding the inclusion distribution during continuous casting of slab.

2. Mathematical Modeling

2.1. Assumptions

(1) There is no slag in the geometry model for simulation. For simplification, the top wall is considered as the slag. The inclusions are removed once they contact the top wall.

(2) The steel is considered as Newton fluid, and the material properties such as density and viscosity are assumed to be constant.

(3) The discrete inclusion generally takes the shape of a sphere. The coalescence of inclusions, and the interactions between the inclusions are completely neglected.

(4) The discrete bubbles also takes the shape of a sphere. The breakage and coalescence of bubbles, and the interactions are also neglected. The bubbles have no expansion.

2.2. Governing Equations

2.2.1. Large Eddy Simulation

The turbulence flow in this work is modeled by Large Eddy Simulation (LES), so as to capture melt flow in detail. In this model, large eddies are directly represented, whereas smaller scale are modeled to solve. Therefore, the large eddies are mathematically filtered and the smaller ones are modeled to close momentum equations. The continuity equation and momentum equation are written as:

Continuity equation:

\[ \nabla \cdot (\rho \vec{\Pi}) = 0 \]  

Momentum equation:

\[ \frac{\partial (\rho \vec{\Pi})}{\partial t} + \nabla \cdot (\rho \vec{\Pi} \vec{u}) = -\nabla P + \nabla \left[ \mu_{\text{eff}} (\nabla \vec{u} + (\nabla \vec{u})^T) \right] - \nabla \tau_{i j} + S_{\text{mol}} + \frac{6}{\pi d_p^3} \cdot F \]  

where \( \rho \) is the density, \( \vec{\Pi} \) is filtered velocity, \( P \) is the static pressure, \( \mu_{\text{eff}} = \mu + \mu_t \) is the effective viscosity of mixture phase. \( \mu \) is the molecular viscosity, and \( \mu_t \) is the turbulent viscosity. The term \( F \) is the source term of two-way coupled Lagrange tracking of particles, which can be written as \( F = F_g + F_b + F_p + F_i + F_{\text{visc}} + F_{\text{diss}} + F_{\text{mol}} + F_{\text{sh}} \). The \( S_{\text{mol}} \) is the source term of momentum force caused by the solidification in mushy zone, which can be defined as:

\[ S_{\text{mol}} = \frac{(1-f_s)^2}{\beta^3} + 0.001 \cdot \text{A}_{\text{mush}} \left( \Pi - \Pi_s \right) \]  

where \( \Pi_s \) is the casting speed, \( \text{A}_{\text{mush}} \) is a mushy zone parameter equal to \( 10^{5} \). \( f_s \) is the liquid fraction, which can be determined from the following part.

The sub-grid scale stress \( \tau_{i j} \) is written as:

\[ \tau_{i j} = \frac{1}{3} \tau_{i k} \delta_{k j} - 2 \mu_t S_{i j} \]  

where \( \tau_{i k} \) is the isotropic part of sub-grid scale stress, which can be neglected because the turbulent Mach number of the flow is quite low; \( \delta_{k j} \) is Kronecker delta; \( S_{i j} \) is strain rate. \( \mu_t \) is the turbulent viscosity determined by the Smagorinsky-Lilly model:

\[ \mu_t = \rho L_s^2 \left( \frac{\| \vec{S} \|}{L_s} \right)^n \]  

where \( L_s \) is the mixing length for subgrid scales, and \( \| \vec{S} \| = \sqrt{2 \frac{\pi d_p}{\rho}} \). In this work, the \( L_s \) is calculated by:

\[ L_s = \min (\kappa d, C_s \Delta) \]  

where \( \kappa \) is a von Kármán constant equal to 0.4, \( d \) is the distance to the closest wall, \( C_s \) is the Smagorinsky constant of 0.2, and \( \Delta \) is calculated based on the volume of the structured cell using \( \Delta = V^{1/3} \). The choosing of \( C_s \) is a little lower than Lilly’s 0.23, as this value was found to cause excessive damping of large-scale fluctuations in the presence of mean shear and in transitional flows as near solid boundary, and has to be reduced in such regions.

2.2.2. Heat Transfer and Solidification

The enthalpy-porosity approach is used to simulate the solidification of steel. It treats the liquid-solid mushy zone as a porous zone. The liquid fraction \( f_s \) is used to describe the mushy zone, which can be defined as:

\[ f_s = \begin{cases} 0, & \text{if } T < T_{\text{solidus}} \\ \frac{T - T_{\text{solidus}}}{T_{\text{liquidus}} - T_{\text{solidus}}}, & \text{if } T_{\text{solidus}} < T < T_{\text{liquidus}} \\ 1, & \text{if } T_{\text{solidus}} < T < T_{\text{liquidus}} \end{cases} \]  

For solidification/melting problems, the energy equation is written as:

\[ \frac{\partial (\rho H_{\text{enthalpy}})}{\partial t} + \nabla \cdot (\rho \vec{\Pi} H_{\text{enthalpy}}) = \nabla \cdot (h \nabla T) + S_e \]  

where \( H_{\text{enthalpy}} \) is the enthalpy of the material, \( S_e \) is source term of energy, which can be written as:

\[ S_e = \rho L_s (1 - f_s) - \rho L_s \frac{\partial f_s}{\partial t} \]  

Here, \( \Pi_s \) is the solid velocity due to the pulling of solidified material out of the domain (also referred to as the casting speed), \( L_s \) is latent heat, \( T_{\text{liquidus}} \) and \( T_{\text{solidus}} \) are liquidus and solidus temperature of steel, and \( h \) is the heat transfer coefficient for water-gas cooling zones (i=0, 1, 2, 3. For instance, \( h_0-h_3 \) represents the foot zone, secondary cooling zone No. 1, No. 2 and No. 3). The equation for calculating
heat transfer coefficients can be found in other works.\textsuperscript{19)}

2.2.3. Inclusion Transport Model

The interactions between inclusion and the steel is two-way coupling, allowing the steel to affect the inclusion, and also, the inclusion to affect the steel. Both the inclusion and steel movements are described in an unsteady state, and also, the inclusion to affect the steel. Both the inclusion two-way coupling, allowing the steel to affect the inclusion, shown in Eq. (10).

\[
m_p \frac{dt}{dt} = F_g + F_b + F_p + F_d + F_l + F_{v-m} + F_{mag} + F_{mar} + F_{th}
\]

The terms on the right hand side of the equation are gravitational force, buoyancy force, pressure gradient force, drag force, lift force, virtual mass force, Magnus force, Marangoni force, and thermophoretic force.\textsuperscript{20)} The thermophoretic force tends to move the inclusion against the temperature gradient, pushing the inclusion towards the solidified shell, but unfortunately, it is usually ignored in previous works. Overall, the forces act on a particle are shown in Fig. 1, and the expressions on the right side of Eq. (10) are summarized in Table 1.

In this work, eight inclusion sizes are defined in the DPM module, ANSYS Fluent 18.0. The inclusion size defined in this simulation is the averaged diameter (70.7 µm, 114 µm, 146 µm, 199 µm, 231 µm, 269 µm, 311 µm, 369 µm) within each diameter bins (50–90 µm, 90–130 µm, 130–170 µm, 170–210 µm, 210–250 µm, 250–290 µm, 290–330 µm, 330–370 µm), and the inclusion number for each bins is 5,000. The choosing of this number is to provide enough inclusions to study, and to avoid accidental error for statistical regularities. What’s more, four bubble diameters are also included, with the values of 0.26 mm, 0.35 mm, 0.75 mm and 1.93 mm, respectively from practical measurements. The bubbles are continuously generated from the inlet of SEN, and the flux of the each bubble size is 2.375 L/min. Other parameters in this work are shown in Table 2.

Table 1. Forces act on the inclusion.

<table>
<thead>
<tr>
<th>Source term</th>
<th>Equation</th>
<th>Annotations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buoyancy force plus Gravity force</td>
<td>( F_b + F_g )</td>
<td>( \frac{(\rho_g - \rho)\pi d^3}{6}g )</td>
</tr>
<tr>
<td>Drag force ( F_d )</td>
<td>( F_d = \frac{1}{8}\pi d^3\rho C_p[\beta - \beta_i]([\beta - \beta_p]) )</td>
<td>where the drag coefficient ( C_p = \frac{24}{Re} (1 + 0.15Re^{0.05}) ), ( Re = \frac{|\beta - \beta_p|\delta}{\rho_p} ) is particle velocity.</td>
</tr>
<tr>
<td>Magnus force ( F_{mag} )</td>
<td>( F_{mag} = \frac{1}{2}A_0C_p\frac{V_{relative}}{V_{relative} \times \Omega_{relative}} )</td>
<td>where ( A_0 ) is projected surface area, ( \Omega_{relative} ) and ( \Omega_{relative} ) are the relative fluid-particle velocity and angular velocity, respectively. ( C_p ) is the coefficient equal to 0.4.\textsuperscript{20)}</td>
</tr>
<tr>
<td>Marangoni force ( F_{mar} )</td>
<td>( F_{mar} = -\frac{2\pi d^3}{3}\left[\frac{\partial \sigma}{\partial T} \frac{dT}{dx} + \frac{\sigma}{\partial C} \frac{dC}{dx}\right] )</td>
<td></td>
</tr>
<tr>
<td>Lift force ( F_l )</td>
<td>( F_l = -\frac{9}{128\mu^3 u^3_s \text{sgn}(G)} \left[\frac{\pi d^3}{\pi d^3}\right]^4 )</td>
<td></td>
</tr>
<tr>
<td>Virtual-mass force ( F_{v-m} )</td>
<td>( F_{v-m} = C_{v-m} \rho \pi \frac{d^3}{dt} )</td>
<td>There are two gravity-related forces,\textsuperscript{19)} the buoyancy force ( F_b ), acts upward; and the gravitational force ( F_g ), acts downward. The net effect acts on the difference between particle and fluid densities. The variable ( g ) is gravity acceleration, ( \delta_p ) is particle diameter, and ( \rho_p ) is particle density.</td>
</tr>
<tr>
<td>Thermophoretic force ( F_{th} )</td>
<td>( F_{th} = -\frac{6\pi d^3\pi^2C_1}{12\left(\frac{d^3}{dt} + \frac{d\pi}{dt}\right)} )</td>
<td>where the thermophoretic force coefficient ( C_{th} = 0.5.\textsuperscript{25)}</td>
</tr>
<tr>
<td>Pressure-gradient force ( F_p )</td>
<td>( F_p = \frac{\rho \pi}{\rho_p \pi \pi} )</td>
<td>The pressure-gradient force is significant when ( \rho/\rho_p \geq 0.1.\textsuperscript{26)}</td>
</tr>
</tbody>
</table>
2.3. Criterion for Inclusion Entrapment

Figure 2 shows the flow chart of inclusion transport and entrapment. When the temperature of molten steel is higher than liquidus temperature (1 800 K), particles can transport in the liquid pool, and the motion of particles, in general, is governed by the gravitational force, buoyancy force, pressure gradient force, drag force, lift force and virtual mass force. When the direction of resultant force points to the mushy zone, the particles would be pushed towards the mushy zone, where the temperature is between liquidus temperature (1 800 K) and solidus temperature (1 760 K). Magnus force and Marangoni force are important for the entrapment of inclusion, and are also considered in our numerical model. In addition to the forces described above, one extra force is exerted on particles that move close to the solidification zone (below 1 760 K), called thermophoretic force. In the current study, it is assumed that particles would be captured if the liquid fraction at the location of particle is below 0.6, because the flow is weak among the dendrites. However, according to previous study, the entrapment of inclusions is a probabilistic phenomenon because the entrapped inclusion may also escape to the liquid zone again when some turbulence happens. So only a constriction of liquid fraction is not enough. As we all know that a low casting speed may help remove more inclusions than a high casting speed, we assure that the casting speed must be taken into account, especially for the small ones. What’s more, the bending arc of slab caster may also contribute to the entrapment ratio of inclusions. So taking all these factors into account, we build an new entrapment criterion: (1) The inclusion must contact the boundary of the liquid fraction of 0.6; (2) The floating velocity of particle should be less than the casting speed; (3) the velocity must have a component that points to the solidified shell, ensuring that the inclusions could be trapped by the dendrites. The detailed description is shown in Fig. 2.

2.4. Boundary Condition and Numerical Details

The computational domain contains five parts: actual mold, foot zone, secondary zone NO. 1, NO. 2 and NO. 3, shown in Fig. 3. The vertical part is above the NO. 2 zone, and the bending part is below it. The submerged entry nozzle is bifurcated, and the shape is shown in Fig. 3. The time-dependent, three-dimensional, filtered Navier-Stokes equations are solved by the SIMPLEC pressure-velocity coupling terms, and the second-order upwind scheme is used for the discretization of momentum terms. Specially, the adaptive-mesh refinement (a mesh schedule embedded in the Ansys Fluent 18.0) was used to capture the flow details near the solidified shell. The refined area is defined as the liquid fraction range from 0.2–0.5 (The liquid fraction of solidified shell is 0.33). The whole domain is divided into $2 \times 10^6$ finite volumes.

A constant velocity boundary condition is applied on the...
inlet of the SEN based on the casting speed (0.6 m/min) of slab caster, and the outlet boundary of the domain is defined as outflow. The top wall of the domain is no-slip, which is regarded as the slag-metal interface. Three inclusion fates are existed in this slab: (1) removed by the top wall of mold; (2) transport in the liquid steel; (3) escape from the outlet of calculation domain. To save calculation time, the current work starts by running a steady-state flow simulation first with a Reynolds-averaged turbulent model, standard k−\(\varepsilon\) model, and then switches to LES once it is converged. The time step size is \(1 \times 10^{-3}\) second, and the total calculating time is 3400 s, which is enough for inclusions moving out of calculation domain.

3. Experimental Inclusion Distribution

Different from previous works for inclusion distribution, a complete in-situ detection is performed based on our Fast-Detection platform (FDP). The slab is acquired from a steel factory, the size of which is 300 mm \(\times\) 2300 mm. It should be noted that because the slab is symmetry about the SEN, the detection on half slab is enough (300 mm \(\times\) 1150 mm). The work schedule for this detecting process is as follows: We peel the slab from outer arc to the inner arc, layer by layer (the cross section is 80 mm \(\times\) 300 mm per layer). Then we detect the inclusions using a microscope that can sweep across the whole surface of the layer. As inclusions are easily found near surface and decays with distance from surface to the center,30 the cutting depth is 1 mm at first, then it gradually increases to 2 mm, and 3 mm to the middle of the slab, shown in Fig. 4. After peeling one layer, we scanned the surface using a 500X scale microscope, and searched for the inclusions. The inclusion morphology would be captured as long as we click the soft button, and it’ll be transferred to the computer screen automatically through the data wire, shown in Fig. 5. The coordinates of inclusions are also read simultaneously. Finally we calculated the equivalent diameter using Image J software.31

3.1. Typical Inclusion Morphology in Steel

Figure 6 shows the in-situ morphology of inclusions along with the surrounding dendrites, after etched by a weak solution of nitric acid and alcohol. Generally, most of the these inclusions are in a singular state, and sometimes gathered into groups or clusters. Bubbles are also found in steel, and the entrapped inclusions are seen inside or around the bubbles. In addition, some special inclusions such as dumbbell-like shape, ring-like shape, are also found and sometimes they can become chains. There’re also colourful inclusions in this slab, but they are quite few. Overall, inclusions are commonly found in a round shape, shown in Fig. 6(i). The reason for this round shape inclusion is because its melting temperature is lower than that of the liquid steel. What’s more, the dendrite arm is bending and bifurcating due to the existence of small particles (see Fig. 6(a)). This kind of dendrites, also known as ‘dizzy dendrites’, are firstly reported by Ferreiro et al.,32,33 when they were investigating the crystallization of polymer blend. They’re also found in steel similarly.

3.2. Space Distribution of Inclusions

Surface defects such as slivers and pencil blisters always result in rejections and downgrading in the final product. Large inclusions (\(\geq 50\ \mu m\)) captured by the solidifying shell are the primary source of those defects.30 And also, it is
impractical to read all-size inclusions in slab, so we mainly focus on the macro inclusion whose size is larger than 50 \( \mu m \). Based on FDP, the inclusion distribution is successfully completed, shown in Fig. 7. The inclusion map contains four aspects (X coordinate-Y coordinate-Z coordinate-Size), in which the sizes are all proportional with each other. It can be seen from Fig. 7 that the macro inclusions are rarely seen at the narrow face of the slab. However, many of them aggregated near the corners of the slab, especially the bigger ones. The reason may be because the corners are cooled from both the narrow side and the wide side, thus it solidifies faster than any other side of the slab. The number of inclusions decreases with distance from the narrow face to SEN. For instance, within 46 mm distance from wide face (0–46 mm), more inclusions are found near the outer arc than the inner arc, while from 46 mm to the center of the slab (46 mm–150 mm), more inclusions are found in the inner arc. From the solidified shell profile at the end of vertical part (shown in the right half of Fig. 7), we can see the inclusions within 46 mm distance from the surface, are mostly trapped in the vertical part of slab caster, while in the region of 46 mm–150 mm, are trapped in the bending part. Thus the distribution shows an opposite regularity in the vertical/bending part. The reason for this special distribution requires serious concern. It’ll be explained in the Section 4, using our mathematical model.

3.3. Comparison of Inclusion Distribution between Vertical/bending Part

Figure 8 shows the percentage of inclusions in the vertical and bending part. Totally speaking, the most inclusions are in a size range between 50 \( \mu m \) and 170 \( \mu m \), which occupies nearly 90% of total inclusions, and that the number of inclusions decreases with the increasing of inclusion size. Specially, the inclusion distribution in the vertical and bending part are quite different: In the vertical part, the inclusions

Fig. 6. Typical morphology of inclusions and surrounding dendrites.
in the outer arc is much more than that in the inner arc, the percentage of which are 41.9% and 28.7%, respectively. However, in the bending part, the inclusions in the outer arc is less than that in the inner arc, the percentage of which are 11.8% and 17.6%, respectively. The inclusion distribution in the vertical and bending part are quite different, showing a special asymmetry distribution in different parts. It is important to study the reason for this special phenomenon, and it’ll be discussed in the next part.

4. Numerical Simulation of Inclusion Distribution

4.1. Validation of Numerical Model

In slab casting, a group of non-contact infrared thermometers are planted near the center of narrow face, along casting speed direction. A non-uniform attribution of these thermometers is adopted to monitor the temperature data near the start/end of solidification zones, as well as the position near the center of the these zones. The total number of these thermometers is 12. Once started, the temperature data would be simultaneously transferred to the computer screen, through online monitoring. For the purpose of model validation, we also predicted the temperature distribution at these points, shown in Fig. 9. The results clearly shows the existence of temperature recovery near the exit of foot zone and secondary cooling zone No.1 and No.2. This phenomenon is because the cooling rate between the two cooling zones are quite different. Generally speaking, the experiment results are uniformly distributed around predicted results. Although there exists some differences between the predicted and the measured values (possibly resulting from the simplified geometry and the uncertainty of material properties, etc.), the predicted temperature agrees well with practical measurements. This validates the mathematical model.

4.2. Evolution of Asymmetrical Flow Pattern

4.2.1. Shell Thickness Distribution

Figure 10 shows the growth of the solidified shell thickness (liquid fraction < 0.33) along the casting direction. It can be seen that the shell thickness increased with the strand length. The shell thickness is rather thin in the center plane, and relatively thick near the corners of the slab. The reason for this phenomenon is because of the cooling conditions of the slab, namely, the corner sides are cooled down from two sides (narrow face and wide face), while the center plane is only cooled down from the wide face.

4.2.2. Evolution of Asymmetrical Flow Pattern

Inclusion movements are greatly influenced by the flow field. So in order to reveal the effect of flow behavior on the distribution of inclusion, the typical flow field is shown in Fig. 11. It can be seen from Fig. 11 that the flow field in the slab is asymmetry and instantaneous, with multiple vortices inside the slab. The jet flow out of the SEN and impinges the solidified shell, forming a typical double-roll flow pattern. The upward melt flows to the top wall of mold, while the downward melt flows to the bottom of the slab, forming ’stair step flow’ inside the slab: At the time of 70 s, the flow biases left, after 10 s, the flow biases right, the same trend is also found in the following times, indicating that the flow biased periodically inside the slab strand, and the period of this flow is about 20 s. This periodical, transient flow makes the multi-scale eddy structure more complex, leading to the fact that the inclusion distribution is asymmetry about the SEN.

4.3. Inclusion Transportation

4.3.1. Predicted Inclusion Distribution

The predicted inclusion distribution is shown in Fig. 12(a). It can be seen that the inclusion distribution is asymmetry
Fig. 7. **In-situ** measurements of inclusion size distribution.

Fig. 10. Solidified shell growth along casting direction (in perspective view).

Fig. 11. Transient flow behavior in the slab.

Fig. 12. Prediction of (a) inclusion distribution and (b) averaged inclusion size in different cooling zones.

Fig. 13. Inclusion/bubble removed by the top wall: (a) inclusion distribution and (b) bubble distribution.

Fig. 14. Inclusion escape from the outlet.
about the SEN, with the percentage of 41.7% and 58.3% in the left and right side, respectively. And comparing with the experimental results in Fig. 7, we can see that even though the predicted position cannot corresponds to the detected result one by one, the predicted result shows a plausibly good regularities with detected result: Large inclusions are accumulated near the corners of the slab, and that there’re few inclusions found in the narrow face. In the vertical part, the inclusions entrapped in the outer arc is much more than that in the inner arc, while in the bending part, the inclusion distribution behaves in an opposite fashion. Similar result are also found in our detection result in Figs. 7 and 8, indicating that our model is feasible for explaining the inclusion distribution in the slab. It is interesting to see that the inclusion size decreases with the distance from the meniscus, just as shown in Fig. 12(b). The reason for this phenomenon may be attributed to the buoyancy force that act on the inclusions, making the big inclusions easier to float up to the mold top and entrapped near the higher positions of this slab caster.

4.3.2. Inclusion Removal/escape Behavior

Figure 13 shows the removal positions of inclusions and bubbles in the mold top. The distribution is obviously random and asymmetry. Nearly 58.7% inclusions in the mold top are entrapped near the outer arc, which is almost 1.5 times of inclusions in the inner arc. This shows that inclusions are easy to aggregate near the outer arc near the mold top, leading to the fact that in the vertical part of slab caster, the inclusions entrapped near the outer arc is much more than that in the inner arc (see Fig. 7). What’s more, large inclusions are tend to be found in the centers, while the smaller ones are everywhere. It is interesting to see the inclusions are quite rare beside the left narrow face, while there exists several near the right side. This shows some stochastic distribution in some certain area. The inclusions are also rarely found in our measurements (Fig. 7), which corresponds to the left side of the slab. Different from the inclusions distribution, the bubble distribution shows a complete different behavior. Large bubbles are tend to be trapped near the center of the slab, especially near the SEN, while the small bubbles are everywhere, showing a relatively uniform distribution near the mold top, shown in Fig. 13(b).

Additionally, the inclusion distribution in the outlet of the calculated region is shown in Fig. 14. It can be seen from Fig. 14 that the inclusions are mostly entrapped near the center of the slab, and the inclusion size is mainly between 70.7 μm and 146 μm, and no inclusions are found bigger than 146 μm. The inclusions are generally very small, however, some inclusions are very close with each other, forming ‘clusters’ near the center of the slab. This is called the “clumps defects”11,35 which is usually found in the center of slabs, and also in our in-situ measurements in Fig. 6. The size of these defects is usually very large, and can make great damage to the properties of final roll product, because they cannot be removed from the center of slab. The inclusions entrapped near the inner arc is much more than that in the outer arc, with the percentage of 87.1% and 12.9%, respectively. The reason is that the inner arc can drag the inclusions floating to the top, just as shown in Fig. 1. All these phenomenon can be described by our LES model, indicating that this model can exactly describe the inclusion movements in slab casting.

4.3.3. Probability Density Function (PDF) of Inclusion Distribution

The prediction of the inclusion size distribution is always a hot topic. Some predictions1,36,37) of the size evolution during secondary steelmaking are reported: power-law size distribution and lognormal size distribution. Different from their works, a new size distribution in slab is shown in Fig. 15, through continuous casting. The predicted result shows a good agreement with in-situ measurements, both qualitatively and quantitatively. Generally speaking, the number of inclusions decreases with the increasing of inclusion size, and many of them are in a range between 50 μm and 90 μm, which ranks first in all the inclusion diameter bins. A majority of inclusion size is smaller than 170 μm (also seen in Fig. 8), and the inclusion larger than 250 μm are quite rare. Based on the experimental results, the probability density function (PDF) of inclusion diameter and percentage can be approximated as Farazdaghi-Harris equation38 shown in Fig. 16. The fitted curve equation for experiment is $f(x) = (1.15 + 4.0928 \cdot 10^{-12} \cdot x^{5.20249})^{-1}$; and for simulation, the fitted equation is $f(x) = (1.25 + 4.0928 \cdot 10^{-12} \cdot x^{5.52049})^{-1}$. The coefficients in the fitted equation have similar format with experiment results, which can also contribute to the reality our our mathematical model.
5. Conclusions

(1) A fast-detection platform (FDP) is successfully established to reveal the complete inclusion distribution in slab. Inclusion distributions in the vertical and bending parts are quite different: In the vertical part, the inclusions in the outer arc is more than that in the inner arc, the percentage of which are 41.9%(outer arc) and 28.7%(inner arc), respectively; In the bending part, the inclusions in the outer arc is less than that in the inner arc, the percentage of which are 11.8%(outer arc) and 17.6%(inner arc), respectively.

(2) The typical morphologies of inclusions are acquired after etched by a weak solution. Dumbbell-like shape, ring-like shape, chains-shape, and golden inclusions are found. They are often in a single state, and sometimes in groups, clusters or chains. What’s more, the inclusions that are entrapped between the dendrites arms are also identified, and that the distortion of dendrite growth caused by the small inclusions, are also found in steel.

(3) Considering nine forces, a new two-way coupled Euler-Langrange mathematical model is established through Large Eddy Simulation (LES). By means of validations about surface temperature, as well as probability density function (PDF) of inclusion distribution, the reliability of our mathematical model is proved.

(4) A new entrapment criterion is established to calculate the inclusion entrapped in the solidified shell. Three factors are included in this criterion: First, the inclusion must contact the boundary of liquid fraction \( f_c = 0.6 \); Second, the floating velocity should be smaller than the casting speed; Third, the velocity must have a component that points to the solidified shell, ensuring that the inclusions could be trapped by the dendrites.

(5) The typical inclusion distribution found through FDP is explained using our mathematical model. From numerical results, we can see an aggregation near the outer arc, leading to the fact that the inclusions in the outer arc is more than that in the inner arc, in the vertical part; However, in the bending part, due to the blocking effect of inner arc, more inclusions are trapped along this arc, leading to the fact that inclusions near the outer arc is much lower than that in the inner arc. What’s more, as inclusions entrapped deeply with the casting speed, they can get together, forming big inclusion ‘clusters’ near the center of slab. This is the reason for the big inclusions found in the center of slab, through FDP.

(6) The removal of bubbles in the mold top is also predicted. Different with inclusions, The big bubbles are tend to be trapped in the center of the slab, near the SEN; While small bubbles are relatively uniformly distributed in the mold top.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (No. 51604070 and 51574068) and the Fundamental Research Funds for the Central Universities of China (No. N162504009).

REFERENCES