Simulations of Macrosegregation with consideration of inclusion effect in solidifying carbon steels

Y F Cao, Y Chen, X H Kang, P X Fu, H W Liu and D Z Li

Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Shenyang, Liaoning, 110016 P. R. China

E-mail: xhkang@imr.ac.cn

Abstract. During casting of steel ingots, the inclusions such as oxide, sulfide will inevitably exist in the melt. These inclusions will flow upward together with light solutes during solidification due to their lower density relative to the steel melt, which therefore causes impacts on the thermo-solutal convection in the melt and final solute distribution. Hence, a macrosegregation model that considers the effects of inclusions on melt flow in the mushy zone is established. Of the new model two important parameters, the inclusion capturing probability by solid, \( k_p \), and the original volume fraction, \( n_0 \), are systematically studied in terms of simulations, which shows that decreasing \( k_p \) or increasing \( n_0 \) leads to stronger ascending flow in the melt. And then as a validation example, the model was used to predict the macrosegregation in a 3.3-ton steel ingot. The prediction demonstrates that with consideration of inclusions, the melt convection strength is enhanced and thus the zones of macrosegregation are expanded comparing to simulations without taking account of inclusions. Further comparison with experiment results indicates that a better agreement of the carbon segregation along the centerline of the ingot can be achieved when considering the inclusion buoyancy.

1. Introduction

Macrosegregation presented as the inhomogeneous solute distributions in very large regions in the final solidified products, is mainly induced by the thermostolutal natural convection, the grain settling or flotation and the shrinkage force of the volume contraction during solidification according to the current theoretical framework. Based on these macrosegregation theories, a large number of numerical simulations have been conducted to predict the chemical variations and inhomogeneities in ingots, such as the multi-component simulation, multiphase simulation, 3D simulation, CAFE simulation and even microstructural level simulation [1-6]. To some extent, these advancing models have a capacity to accurately predicate the formation of macrosegregation in common model alloys, such as Sn-Pb, Sn-Bi, Al-Cu, Ga-In and Ni-base superalloy [4, 7-10], but significant discrepancies between simulations and experiments still persist in solidifying steels [11]. For example, the positive segregation at the hot-top is usually underestimated in simulations, and the shape and segregated carbon content at the bottom negative cone-segregation zone in simulations are much different from experimental measurements. Most significantly, nearly most of the numerical computer simulations cannot reproduce “A-type” channel segregates at the upper-middle part of the steel ingot body. It is definite that the density difference in the melt that leads to the macrosegregation, however, in steel ingots, the difference not only can be resulted by the solute and temperature, but also induced by the solidified equiaxed crystals and the existing inclusions. For the sedimentation of grains, the effects
have been well investigated through numerical simulations [2, 3, 12-14], whereas for the effect of impurities and inclusions, it has been neglected for a long term.

Recently, the systematic investigations of experiment and multi-scale simulations of channel segregation in a series of sectioned steel ingots by Li and coworkers [15] have demonstrated strikingly that the A-segregation is actually a zone with enrichments of small Al2O3 and MnS inclusions except for the accumulated massive amount of solutes. Their contrast experiments also have shown that decreasing the content of alumina-based inclusions will be beneficial to eliminating the A-segregation in steels. These experiments seem to be right to interpret the channel segregates in steel ingots, because the amount of main solute carbon that drives the melt flow usually is orders of magnitude smaller than that in the often used model alloys (i.e. Pb-Sn, Pb-Bi, Ga-In, Al-Cu and Ni-base superalloy) in experiments and simulations, and hence the density difference in the melt of extensively applied steels cannot drive sufficiently strong convection in the interdendritic region to destabilize the mushy zone and promote the formation of segregation channels. As the inclusion content reaches a high level, the influence of light non-metallic inclusions on the liquid flow, and eventually on the formation of macrosegregation, should be concerned adequately.

Accordingly, a continuum macrosegregation model rather than the multiphase flow model as illustrated in Ref. [15] for describing the transport phenomena in solidification systems, including the effects of inclusions, is presented in this paper. A systematic examination on inclusion parameters of the built model is demonstrated in detail. And then, as an application the developed model is employed to simulate the flow field and macrosegregation formation in a typical 3.3-ton steel ingot.

2. Macrosegregation model

In this paper the two-dimensional calculations are carried out and some main assumptions in current developed model are listed: (1) solidified grains are supposed to be columnar and the solid movement and shrinkage are not considered; (2) the liquid is Newtonian and incompressible while the convection is laminar; (3) the effect of diffusion on the solute transport is also neglected; (4) Boussinesq approximation is used to account for buoyancy driven flow, including the effect of inclusions. On the basis of these hypotheses, the mass, momentum, mixture energy, mixture solute and inclusion conservations are described as follows.

2.1. The mass, energy and solute governing equations

Conservation of mass:
\[
\nabla \cdot \left( \overline{\rho U} \right) = 0
\]
\[
\overline{U} = (1 - f_s)\overline{U}_l
\]

Conservation of energy:
\[
\frac{\partial \left[ \rho H \right]}{\partial t} + \nabla \left( \rho c_p \overline{U} T + \rho \overline{U} \Delta H \right) = \nabla \cdot \left( \lambda \nabla T \right)
\]
\[
\left[ \rho H \right] = f_s \rho_s h_s + (1 - f_s) \rho_l h_l
\]

where \( \rho \) and \( f_s \) are the mixture density (equal to solid and liquid density of steel) and solid fraction respectively, \( h_s, h_l, H \) and \( \Delta H \) are the solid, liquid, mixture enthalpy and latent heat respectively, \( c_p \) and \( \lambda \) are the specific heat and heat conductivity respectively.

Conservation of solute:
\[
\frac{\partial [C]}{\partial t} + \nabla \cdot \left( \overline{U} C_j \right) = 0
\]
\[
[C] = \int_0^{f_s} C_s \, d\alpha + (1 - f_s) C_l
\]
where $\{C\}, C_s$ and $C_l$ are the mixture, solid and liquid concentrations respectively, and $f_s$ and $\vec{U}_l$ are the solid fraction and liquid velocity vector during solidification.

### 2.2. The conservation equations of inclusions and momentums

In this study, alumina particles are assumed with a very small diameter (i.e., $< 5\sim 10$ μm) so that they can’t float up quickly according to Stokes’ law, and most of them may move with the liquid. Such fine alumina particles in the melt mostly stem from the adoption of aluminum deoxidation technique during the refining process. This assumption is reasonable because the dissolved oxygen content in steel melt is very low (usually $< 5\sim 10$ ppm), therefore, the formation of alumina at the solidification stage is negligible. And all the pre-existing alumina particles are distributed evenly in the ingot before solidification. During real solidification, because of the blocking of dendritic networks and trapping of solidified crystals, a certain proportion of alumina cannot be rejected into melt and has neglected contribution to the liquid flow. Therefore, an artificial partition coefficient $k_p$, similar to the solute partition between solid and liquid, is introduced to depict the probability of the trapped inclusions by solid in a given control element.

**Conservation of inclusions:**

$$\frac{\partial n}{\partial t} = \nabla \cdot (\vec{U} n_l)$$  \hspace{1cm} (7)

$$n = n_s f_s \int d\alpha + (1 - f_s) n_l$$  \hspace{1cm} (8)

where $n, n_s$ and $n_l$ are the mixture, solid and liquid volume fractions of inclusions in a specific control element, respectively.

**Conservation of $u$ momentum (X direction):**

$$\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho \vec{u} u) = -\frac{\partial P}{\partial x} - \frac{\mu}{K} \nabla \cdot (\mu \nabla u)$$  \hspace{1cm} (9)

**Conservation of $v$ momentum (Y direction):**

$$\frac{\partial (\rho v)}{\partial t} + \nabla \cdot (\rho \vec{u} v) = -\frac{\partial P}{\partial y} + \frac{\mu}{K} \nabla \cdot (\mu \nabla v) + \rho g \left[ \beta_T \left( T - T_0 \right) + \beta_C \left( C_i - C_0 \right) \right] + \rho g \beta_p (n_l - n_0)$$  \hspace{1cm} (10)

$$\rho = \rho_p n + \rho_{Fe-C} (1 - n) \Rightarrow \frac{\rho}{\rho_{Fe-C}} = \frac{\rho_p}{\rho_{Fe-C}} n + 1 - n = 1 - (1 - \frac{\rho_p}{\rho_{Fe-C}}) n \Rightarrow \beta_p = \frac{\rho_{Fe-C} - \rho_p}{\rho_{Fe-C}}$$  \hspace{1cm} (11)

where $\beta_T, \beta_C$ and $\beta_p$ are the thermal, solute and inclusion expansion coefficient respectively. $T_0, C_0$ and $n_0$ are the initial liquidus, solute concentration and inclusion volume fraction, respectively. $\rho_p$ and $\rho_{Fe-C}$ are the inclusion and steel density respectively. $K$ is the permeability in the mushy zone according to Carman-Kozeny formula:

$$K = \frac{d_s^2 (1 - f_s)^3}{180 f_s^2}$$  \hspace{1cm} (12)

where $d_s$ is the secondary dendritic arm spacing.

### 2.3. The calculation of solid fraction

The local thermodynamic equilibrium at the solid-liquid interface is guaranteed by assuming that the temperature at the liquid side is equal to the liquidus temperature of the melt:

$$T = T_m + m_l C_i$$  \hspace{1cm} (13)
And therefore, in combination with Eqs. (3), (4), (6) and (13) the solid fraction can be eventually obtained, which yields to a quadratic equation of solid fraction $f_s$

$$A \cdot (f_s^{t+\Delta t})^2 + B \cdot f_s^{t+\Delta t} + E = 0 \quad (14)$$

Here the coefficients are written as,

$$A = (1 - k) \rho \Delta H$$

$$B = \rho \Delta H (k \cdot f_s^t - 2) + (k - 1) (\rho c_p T_m - [\rho H]^t)$$

$$E = (\rho c_p T_m - [\rho H]^t + \rho \Delta H)(1 - f_s^t) - \rho c_p m_i C'_i (1 - f_s^t) \quad (15)$$

where $k$, $T_m$ and $m_i$ are solute partition coefficient, melting point of iron and liquidus slope respectively, superscripts $t$ and $\Delta t$ are time and time step, respectively.

### 2.4. Numerical implementations

In calculations, an explicit scheme of finite volume method is used to solve the coupled equations for momentum, solute, inclusion and heat transports. The solution algorithm for transient fluid flow technique is employed to solve the Navier-Stokes equations. A carbon steel ingot which has a weight of 3.3 ton is used in simulations. The specification of the thermal boundary conditions at outer and inner surfaces and initial conditions can be referred to the paper by Combeau et al. [16]. The input parameters for calculations are compiled in table 1. The simulations of the solidification process are performed first with different partition coefficients, $k_p$ and original volume fractions of inclusions, $n_0$ to investigate the response of these inclusion parameters on the liquid flow intensity. And then the macrosegregation of a steel ingot that takes account of inclusion buoyancy is investigated.

| Table 1. The main parameters used in simulations. |
|--------------------------------------------------|
| Solutal expansion coefficient, $\beta_C$               | $1.4164 \times 10^2$ wt.%$^{-1}$ |
| Thermal expansion coefficient, $\beta_T$              | $1.07 \times 10^4$ K$^{-1}$ |
| Liquidus slope, $m_i$                                | $-80.45$ K wt.%$^{-1}$ |
| Inclusion expansion coefficient, $\beta_p$           | 0.48 |
| The spacing of secondary arm, $d_s$                  | 500 $\mu$m |
| Dynamic viscosity, $\mu$                             | 0.0042 Pa s |
| Specific heat, $C_p$                                 | 500 kg$^{-1}$K$^{-1}$ |
| The latent heat, $\Delta H$                          | 271000 J kg$^{-1}$ |
| The thermal conductivity, $\lambda$                 | 39.3 W m$^{-1}$K$^{-1}$ |
| The steel density, $\rho$                            | 6990 kg m$^{-3}$ |
| The melting temperature, $T_m$                       | 1532 $^\circ$C |
| Solute partition coefficient, $k$                    | 0.314 |
| Inclusion partition coefficient, $k_p$               | 0.2, 0.4, 0.6, 0.8 |
| Initial inclusion volume fraction, $n_0$             | 0.002, 0.004, 0.006, 0.008, 0.01 |
| Grid size                                          | 10 mm $\times$ 10 mm |
| Inclusion density, $\rho_p$                         | 3640 kg m$^{-3}$[17] |

### 3. Numerical Results and discussion

#### 3.1. The effect of inclusion partition coefficient $k_p$

During solidification of steel ingot, some of small pre-existent inclusions will be captured by the solid dendritic network. This phenomenon as described above in the present model is characterized by a phenomenological partition coefficient, $k_p$. However, it is difficult to measure the capturing probability in experiments, and thereby a region of the partition coefficient ($k_p = 0.2 \sim 0.8$) are chosen in calculations to investigate the trapping effect induced by solid. In these calculations the original volume fraction of inclusions is supposed to be as high as 0.01 [18]. The contribution of solute carbon
on the buoyancy-driven flow is excluded in the simulations for clearly understanding the liquid flow intensity induced by inclusions. Figure 1 shows the simulated liquid flow field and the solid fraction after freezing of 2505 s. At this time almost half of the ingot body has been solidified and the thermal-inclusion buoyancy force induced liquid convection has reached a stable evolution tendency. Initially, due to the chilling of walls, the melt is cooled fast near the wall and a sharp thermal gradient is built up. Hence, the cooled melt resulted from the thermal contraction has a higher density and moves downwards along the chilling wall, while the hotter melt that is relatively lighter in the center moved upwards. With the solidification proceeding, the heat extraction from the walls becomes inefficient due to the thicker solid shell of the ingot. And the thermal boundary layer ahead of the solidification front is therefore thick, which induced a weaker thermal flow in the liquid comparing with that at the onset of solidification. Furthermore, owing to the rejection of inclusions from the solid to liquid, more and more inclusions are accumulated before the solidification front. This lighter substance would thus lead to the liquid flow upwards in and nearby the mushy zone. In contrast to the thermal convective flow, this ascending flow becomes more intense accompanying with the solid growth. Consequently, after solidification for several minutes (about 300 s in current simulation), when the volume fraction of enriched inclusions reaches a certain value and satisfies

$$|\beta_T(T - T_{ref})| < |\beta_p(n - n_0)|$$

(16)

the flow leaded by inclusion buoyancy force will overwhelm that leaded by thermal buoyancy, and reverses the flow direction of melt in the ingot, that is a clockwise flow on the left half of the entire ingot as shown in figure 1. Afterwards, the overall liquid flow is dominated by the inclusion almost until the end of solidification, playing a similar role of solute carbon on the liquid convection.

![Figure 1. The simulated liquid flow and solidification profiles at 2505 s with different $k_p$, and $n_0$ is 0.01. Left: liquid flow velocity; Right: solid fraction. (a) $k_p = 0.2$, (b) $k_p = 0.4$, (c) $k_p = 0.6$, (d) $k_p = 0.8.$](image)

When comparing the simulations between different partition coefficients, $k_p$, the flow patterns rarely can be observed significant distinctions, but the flow intensity increases with the decrease of $k_p$. Even though small amounts of inclusions are discharged into the melt, e.g. for the simulation $k_p = 0.8$ shown in figure 1(d), the liquid convection is still dominated by the displacement of inclusions. It should be mentioned that the mushy ranges are rather narrow in all cases, this is caused by neglecting the solute effect in the simulations and heat conduction can proceed very easily compared with solute transport.
In order to quantitatively evaluate the influence of the parameter $k_p$ on convection strength, the interdendritic average velocity $|U|$ in the mush of ingot body, defined as a zone with a solid fraction between 0 and 0.7, are calculated as listed in table 2. Apparently, the flow velocity decreases monotonously with increasing coefficient $k_p$, but the change is not pronounced. This result further confirms that with the decrease of $k_p$, more inclusions will not be captured by solid phase and enter the residual melt adjacent to the solidification front. As a result, the larger amounts of light inclusions lead to higher buoyancy force and thus stronger convection.

**Table 2.** The interdendritic average flow velocity in the ingot body with different $k_p$ at 2505 s.

| $k_p$ (cm/s) | 0.2 | 0.4 | 0.6 | 0.8 |
|-------------|-----|-----|-----|-----|
| $|U|$ (cm/s)  | 0.0422 | 0.0326 | 0.0238 | 0.0136 |

3.2. The effect of initial inclusion volume fraction $n_0$

In steelmaking industry, minimizing the inclusion content is always an essential target to prevent cracks or fatigue fractures and even alleviate macrosegregation, specially channel segregation [15]. For the sake of understanding the role that inclusions play, the effect of initial inclusion volume fraction on macrosegregation is investigated. Figure 2 denotes the velocity field and solid fraction at 2505 s in case of inclusion partition coefficient being assumed as 0.2, which indicates obviously that stronger convection is resulted in the bulk melt and the mushy zone as initial inclusion volume fraction increases. Quantitatively, table 3 gives the average melt flow velocity $|U|$ with different $n_0$.

**Table 3.** Average velocity of solidification front in ingot body with varied $n_0$ at 2505 s.

| $n_0$ | 0.002 | 0.004 | 0.006 | 0.008 | 0.01 |
|-------|-------|-------|-------|-------|-----|
| $|U|$ (cm/s) | 0.012 | 0.0205 | 0.0286 | 0.035 | 0.0422 |

The average velocity variation in table 3 shows that, when $n_0$ varies from 0.002 to 0.01, the velocity magnitude increases to 0.0422 from 0.012 cm/s, which can be naturally comprehended as the following situations are taken into consideration: Given the same thermal conditions, when solid zone occupies half of the whole ingot, there will be more inclusions advected into the un-solidified zone and more serious accumulation of inclusions forms with increasing $n_0$, which causes a greater density difference between the interdendritic melt and bulk liquid. Therefore, a stronger driving force of upward flow and higher velocity in the mushy zone are induced.

![Figure 2.](image-url)
It is worthy of noticing that except for these two most important parameters of inclusions that affect the liquid flow, the size and shape of an inclusion particle which are usually important characteristics of a solid particle moving in liquid, are not considered in the present simulations. Indeed, the motion of a solid inclusion particle is governed by a balance of buoyancy force, drag force, virtual mass force, Saffman’s lift force and other forces and therefore the particle has its own velocity that is locally different from the liquid flow velocity. The moving of particle separately, in turn, will impact the flow of fluid phase, especially the localized flow around the particle. In regard to the shape of a particle, the more complicated shape of the surface, the larger frictional force is acted upon by the liquid; hence the lower moving velocity of melt is dragged. Physically, the particle moving kinetics in liquid dependent on the shape and size actually falls into the category of liquid-solid two phases flow problem, however, in the current model to make the problem to be feasible for simulation, the inclusion and the melt are treated as the same phase but have different densities. Therefore, the divergence stemming from the simplification of the model exists to some extent for inclusion that has a large size and smooth surface. With including this fluid-structure and fluid-inclusion interactions, an improved model combining with an accurate description of the motion of inclusions in steel melt using a Lagrangian approach will be developed in the future work.

3.3. Prediction of macrosegregation in a carbon steel ingot with consideration of inclusions

Based on above examination of the established model, it is then extended to simulate and predict carbon macrosegregation in a Fe-0.36 wt.% C steel ingot. Figure 3 shows the final carbon and inclusion distribution maps with a range of the partition coefficient $k_p (0.2$–$0.8)$ assuming the original inclusion volume fraction of 0.01. On the whole, the typical positive segregation at the upper ingot, the characteristic conical negative segregation at the bottom and the stripe-like channel segregation in the riser induced by the destabilized mushy zones are all predicted in the four different simulation cases, which agrees well with the simulation results in Ref. [16]. These results further demonstrate that both the positive and negative segregation zones are expanded and become more serious as the inclusion partition coefficient decreases. Similarly, figure 4 provides the predicted final carbon and inclusion segregation patterns with different $n_0$, where $k_p$ is assumed as 0.2. The predicted segregation pattern is analogous to that shown in figure 3. Moreover, it indicates that the positive segregation at the hot-top and the cone-shaped negative segregation at the bottom are severer with the increase of original inclusion volume fraction. In addition, the inclusion distribution patterns are identical to that of carbon, and inclusion inhomogeneity becomes severer with increasing $n_0$ and decreasing $k_p$. The distribution consistency between carbon and inclusion is decided by the assumptions in current applied model, where the similar inclusion behavior with solute is considered and described (see section 2.2).

In order to further quantitatively examine the effect of inclusion partition coefficient and original volume fraction on the carbon macrosegregation, the global extent of macrosegregation $GM$ [1] is introduced (Eq. 17) and figure 5 plots the calculation results of $GM$ in full ingot and ingot body respectively with various $k_p$ and $n_0$.

$$GM = \frac{1}{C_0} \left[ \frac{1}{V_{\text{casting}}} \iiint (C - C_0)^2 \, dV \right]^{1/2}$$  \hspace{1cm} (17)$$

Figure 5(a) shows that the severity of $GM$ exhibits a dependence on the inclusion partition coefficient closing to a linear relationship, and the extent of $GM$ becomes severer as $k_p$ decreases. The decreases of $k_p$ indicates that less inclusions will be trapped by the solid sketch, and more inclusions will segregate into the mushy zone and liquid during solidification. The segregated inclusions, together with carbon, cause a more intensive upward buoyancy force because of their less density and larger driving force. Consequently, the solute can move not only in a larger distance and regions but also with higher quantity. Eventually, larger amounts of solutes are taken away by melt flow from the side and bottom of the ingot into the center and top part; meanwhile solute-lean liquid will enter the bottom from the centerline and a solute depleted region is initiated. Similarly, the large carbon
segregation caused by increasing \( n_0 \) (figures 4 and 5(b)) can be explained due to the larger density difference between interdendritic melt and bulk liquid. In addition, of all the simulation cases the global macrosegregation in full ingot is no except severe than that in ingot body and inclusion buoyancy indeed increases the segregation of carbon compared with case neglecting the inclusion effect as shown in figure 5(b).

![Figure 3](image1)

**Figure 3.** Final carbon (left) and inclusion (right) distribution maps with different inclusion partition coefficients \( k_p \). Here, \( n_0 = 0.01 \) and (a) \( k_p = 0.2 \), (b) \( k_p = 0.4 \), (c) \( k_p = 0.6 \), (d) \( k_p = 0.8 \).

![Figure 4](image2)

**Figure 4.** Final carbon (left) and inclusion (right) distribution maps with different original inclusion volume fractions \( n_0 \). Here, \( k_p = 0.2 \) and (a) \( n_0 = 0.01 \), (b) \( n_0 = 0.008 \), (c) \( n_0 = 0.006 \), (d) \( n_0 = 0.004 \), (e) \( n_0 = 0.002 \).

Besides the global macrosegregation the solute segregation along the centerline is more serious than other zones and usually is used to characterize the composition segregation extent of a steel ingot. Figure 6 shows that the severity of positive and negative segregations along the centerline become larger when \( k_p \) decreases or \( n_0 \) increases. This is closely connected to stronger convection induced by the more segregated inclusions in the mushy zone (figures 3 and 4). The experimental measurements
of carbon concentration [16] and the simulation result without inclusions are also presented in figure 6(b). The predicted carbon content at the hot top with a model not considering the effect of inclusions underestimated the experiment result, whereas the current model with consideration of inclusions can overshoot the experimental data, even though the original fraction of inclusions is as low as 0.002. This is plausible that in actual production of the experimental ingot, the inclusion content may be far below this level due to the refining techniques used before the pouring process, in which case the carbon distribution will become more uniform because of weaker convection in the mushy zone rather than being such overestimated as shown in figure 6(b). Therefore, we can postulate that taking into account the contribution of inclusions on the buoyancy force, a better agreement can be achieved with experiment at the top positive segregation zone when appropriate $k_p$ and $n_0$ are chosen.

Figure 5. The global extent of macrosegregation (GM) in the ingot: (a) varied inclusion partition coefficients $k_p$ with $n_0 = 0.01$; (b) varied original inclusion volume fractions $n_0$ with $k_p = 0.2$.

Figure 6. The predicted final carbon macrosegregation along the centerline of the ingot: (a) $n_0 = 0.01$ with variation of $k_p$; (b) $k_p = 0.2$ with variation of $n_0$. The inset diagrams show the magnified part of curves at the bottom part of the ingot.

4. Conclusions
A new mathematical model of macrosegregation including the effect of inclusions on the buoyancy
force has been presented. The inclusion induced flow and the subsequent solute segregation during solidification were investigated in detail through numerically solving the governing equations. In terms of simulations, especially the effect of two important parameters (inclusion capturing probability, \( k_p \) and original inclusion volume fraction, \( n_0 \)) on the flow field during solidification were firstly examined and then the model was applied to predict carbon macrosegregation pattern with different \( k_p \) and \( n_0 \) in a 3.3 ton steel ingot. The analysis and discussion on the model and application allowed for the following main conclusions. Firstly, large \( n_0 \) and small \( k_p \) both favor the upward flow in the mushy zone during the stage that solute-inclusion buoyancy force dominates the melt convection, and the average velocity of interdendritic melt can reach as high as 0.0422 cm/s even though it is free from the influence of solutes. Secondly, the model successfully predicts the carbon macrosegregation pattern, including the positive segregation at the hot top, the cone-shaped negative segregation at the bottom and A-type segregation in the riser of the steel ingot. The simulation results also demonstrate that large \( n_0 \) and small \( k_p \) will make the global macrosegregation larger and the segregation along the centerline severer. Compared with experiment results, the model with the effect of inclusions enhances the melt convection strength and results in higher ratio of segregation along the centerline at the hot top of the ingot, which is always underestimated by previous macrosegregation models, so that better agreement can be achieved between simulation and experiment when appropriate \( k_p \) and \( n_0 \) are chosen rather than the current arbitrary values used.

However, the present explorative model should be viewed as a preliminary understanding of the influence of inclusion (or impurity) on the liquid flow during solidification of steel ingot and the subsequent macrosegregation. Clearly, the practical solidification process is much more complicate than present simulations and many other important aspects should be considered in the elementary models, such as, the effect of sedimentation of free equiaxed crystals, the accurate description of the interaction between dispersed inclusions and continuous phase, mutual interactions between inclusions, different kinds of inclusions (manganese oxide, sulfide, etc.) and crystal growth.

**Acknowledge**

This work is supported by National Natural Science Foundation for Young Scientists of China (Grant No. 51401223) and National Natural Science Foundation of China (Grant No. 51271184).

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