Numerical Modelling of Inclusion Behaviour in a Gas-stirred Ladle

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The treatment of liquid metal in gas-stirred ladles has long been identified as the main process responsible for the inclusion cleanliness in special steels. Four university teams and three steels developers have combined their efforts through a project, supported by French National Research Agency, in order to improve the understanding of the complex mechanisms involved during the ladle treatment. In this paper, the contribution of the Institut Jean Lamour to this program, that bears the acronym CIREM, is presented. Using a commercial CFD code as a basis, a three-dimensional simulation model is developed that includes the geometry and industrial operating conditions. The hydrodynamics of the turbulent metal/bubbles mixture is well represented along with the coupled mechanisms of transport, aggregation and surface entrapment of inclusions.

KEY WORDS: inclusion; liquid steel; simulation; population balance.

1. Introduction

The control of metal cleanliness represents a major challenge for steel producers, because it affects both product quality and lifetime of processing tools. Lowering the weight of finished parts, continuously improving the mechanical properties and increasing the recycling of used metal, make the metal cleanliness an unavoidable issue. Gas stirring ladle treatment of liquid metal has been pointed out for a long time as the processing stage mainly responsible for the inclusion population of specialty steels. The successive steps of that process are deoxidising (where most oxide inclusions are generated), degassing, further chemical additions, and inclusion removal by floatation and settling.

A better understanding of the behaviour of the inclusion population can only be achieved through the combination of studies at the interfacial scale, where the behaviour of an inclusion is driven by the influence of a nearby surface, and at the scale of the metallurgical unit, where macroscopic transportation and mass transfer mechanisms play a prominent role.

This work is the development, using a commercial CFD code as a basis, of a three-dimensional simulation model taking into account the industrial geometry and operating conditions. The hydrodynamics of the turbulent metal/bubbles mixture is well represented along with the coupled mechanisms of transport, aggregation and surface entrapment of inclusions. This work integrates the results produced by the other teams (such as the kinetics of aggregation or capture). In the next chapter the state of the art in numerical simulation of inclusion population is drawn up with the aim of positioning the present work.

2. Description of the Metallurgical Process and Modelling Approach

Before die casting or continuous casting, liquid steel is treated in a gas-stirred ladle as shown in Fig. 1. The ladle is positioned in a sealed vessel and a primary pumping device allows the pressure to reach about 1 mbar. The degassing operation eliminates or reduces the dissolved gaseous components (nitrogen, oxygen, hydrogen) and removes sulphur from the steel. In order to deoxidize the bath, elements such as aluminium or calcium are introduced in the form of cored wires (Fig. 1). Finally, an injection of argon through one or more porous plugs at the bottom of the ladle provides both mixing of the liquid metal to achieve thermal and chemical homogeneity and the entrapment of the inclusions by the bubbles known as the floatation mechanism.

The gas-stirred ladle is a complex three-phase reactor, where the strongly dispersed inclusions are transported by the turbulent liquid metal/bubbles flow. A precise descrip-

Fig. 1. Schematics of a ladle refining facility with degassing.
tion of the large number of interactions is necessary in order to obtain a good representation of the evolution of the inclusion population during the treatment. The mechanisms involved are:
- the collisions between inclusions, which can lead to aggregation and even to agglomeration if reconstruction of the aggregate occurs,
- the collisions with bubbles, which lead to the mechanism of floatation,
- the entrapment at the interface between the liquid bath and slag coverage,
- the entrapment at the ladle walls.

The modelling of the liquid steel ladle has already been the subject of many studies. Until the late '80s, research on inclusion cleanness has been divided between thermodynamic studies aimed to determine the experimental equilibrium slag-metal-inclusion\textsuperscript{1} and the first calculations on secondary metallurgical reactors.\textsuperscript{2}

Since the '90s, the knowledge of thermo-chemical equilibrium has been capitalized on and has given birth to computing software, now widely used in the steel industry to predict the composition of stable phase inclusions.\textsuperscript{3} Furthermore, the simulations of liquid metal processing were developed with an increasing level of sophistication. This type of work, performed under the leadership of KTH in Stockholm\textsuperscript{4} and the University of Urbana-Champaign,\textsuperscript{5} can be considered as a benchmark in this field. A fairly comprehensive and recent presentation of the modelling approaches is given by Zhang\textsuperscript{6} and an application to the aluminium industry is given by Mirgaux et al.\textsuperscript{7,8} However, most models used by these authors should be regarded as general models of processes that do not accurately describe the behaviour and the capture of particles at interfaces (refractory wall, surface and bubbles). Among the few experimental studies in this field, the contribution of Tohoku University\textsuperscript{9} represents a laudable effort in order to make original experiments in hot or cold models. The innovative experiment of Xie et al.\textsuperscript{10} often referred to as the “Oeters' ladle”, to measure the hydrodynamics of a metal bath stirred by argon bubbles is an important contribution to this research. This comprehensive work has been appreciated by experts in numerical simulations\textsuperscript{11} who have made use of the experimental data for model validations.

In this paper, the approach adopted for reactor modelling is divided into two parts. The bubbles plume and the porous injectors play an important role in metal bath mixing while, owing to their small weight fraction (<0.01%), the inclusions do not affect the flow. First, the two-phase flow turbulent bubble-liquid steel is simulated for the 3D geometry of the ladle and a strong coupling is achieved between the liquid metal and the bubbles. This resolution provides the velocity fields as well as the maps of local flow turbulence and retention rate \( \alpha \) (gas volume fraction in the mixture); these data define the conditions of inclusion interaction (aggregation, floatation, entrapment). This hydrodynamic model has been applied to the Oeters' ladle and comparisons have been set up with the experimental measurements on the one hand and with the numerical results provided by Aoki et al.\textsuperscript{13} on the other hand. In the second step, the behaviour of the inclusion population is accountable to both the transport at the macroscopic scale of the ladle and the interaction mechanisms at the mesoscopic scale of the particle. The general equation of population balance is solved in the same 3D geometry by coupling a discrete class method with the finite volume method. Therefore the numerical simulation provides an accurate description in macroscopic and mesoscopic scales and can be considered ahead in this field. Finally the behaviour of an inclusion population in the Oeters’ ladle is simulated and the effects of the different interaction mechanisms are discussed.

3. Ladle Modelling

3.1. Hydrodynamic Modelling of the Liquid-bubbles Mixture

The modelling of liquid-gas flows, applied to ladle treatment of molten steel, is treated in literature using either the Euler-Euler method\textsuperscript{12,14} or the Euler-Lagrange method.\textsuperscript{15-17} Each approach has equally important advantages and drawbacks. We have chosen the Euler-Euler approach which guarantees a gas fraction in the interval [0:1]. Moreover the main advantage of this approach is that inclusion transport, coupled with the population balance equation, can be calculated without the use of any post-processing operation.

Following this approach, the dispersed phase (gas) is governed by a set of transport equations (continuity (1) and momentum (2)) similar to the equations applied for the continuous phase (liquid). This model, called the “two fluids model”, is given by:

\[
\frac{\partial}{\partial t}(\alpha_k \rho_k) + \nabla \cdot (\alpha_k \rho_k \mathbf{u}_k) = 0 \quad \text{and} \quad \ldots \\
\frac{\partial}{\partial t}(\alpha_k \rho_k \mathbf{u}_k) + \nabla \cdot (\alpha_k \rho_k \mathbf{u}_k \mathbf{u}_k) = -\alpha_k \nabla p + \alpha_k \rho_k \mathbf{g} + F_k
\]

The index \( k \) stands for each phase, liquid or gas, \( \alpha_k \) is the retention rate of the phase \( k \) and \( \rho_k \) its density, \( d_k \) is the equivalent gas bubbles diameter, \( \mathbf{u}_k \) the average velocity vector and \( \mathbf{g} \) the tensor of viscous stresses. The local pressure \( p \) is assumed to be identical in each phase. \( F_k \) represents the interaction force (reported by unit volume of fluid) between the two phases (\( F_1 = -F_0 \)), combining the two sets of equations for the liquid and gas phases. Four forces were identified: drag (\( F_{\text{drag}} \)), lift (\( F_{\text{lift}} \)), added mass (\( F_{\text{mass}} \)), and turbulent dispersion (\( F_{\text{disp}} \)). Therefore \( F_k \) is expressed as the sum of the four contributions \( F_{\text{drag}}, F_{\text{lift}}, F_{\text{mass}} \) and \( F_{\text{disp}} \).

3.1.1. Drag and Lift Forces

The drag force acts in the direction opposite to the bubble-liquid relative slip velocity. This force represents the predominant resistance to the upward movement of gas bubbles in the liquid bath. The expression used is:

\[
F_{\text{drag}} = \frac{3}{4} C_D \alpha \rho_l (u_g - u_l) |u_g - u_l|
\]

The drag force plays a very important role in the motion of bubbles in the plume. Therefore special attention has been reserved to accurately estimate the drag coefficient \( C_D \) appearing in Eq. (3). The bubbles in the liquid steel ladle have a very important equivalent diameter (assumed to be only dependent on the metallostatic pressure), and have the
shape of a spherical cap (Eötvös number reaches values near 40). Under these conditions the drag coefficient \(C_D\) reaches a constant value, equal to 8/3 as stated by Ishii and Zuber.\(^{17}\)

The lift force acts perpendicularly to the sliding velocity between the two phases, and may lead, according to its sign, either to bubble dispersion or plume contraction. The expression to calculate the lift force is:

\[
F_L = \rho_i \cdot C_L \cdot (u_g - u_l) \times (\nabla \times u_l) \quad \text{............ (4)}
\]

where \(C_L\) is the lift coefficient. In order to obtain the lift coefficient we decided to use the Tomiyama et al. correlation\(^{18}\) that takes into account a large spectrum of bubble shapes. For large diameter bubbles, the lift force has a tendency to concentrate the bubbles along the axis of the plume as \(C_L\) becomes negative.

3.1.2. Added Mass Force

The calculation of the added mass force is expressed as follows:

\[
F_{AMD} = \rho_i \cdot C_{AMD} \left( \frac{D_t u_g}{D_t} - \frac{D_t u_l}{D_t} \right) \quad \text{............ (5)}
\]

where \(D_t/D_t\) is the material derivative for each phase and \(C_{AMD}\) is the added mass coefficient, taken here equal to 0.5.

3.1.3. Turbulence

The standard \(k-\epsilon\) model is used to calculate the turbulence of the continuous phase (liquid steel). In this Reynolds Averaged Navier-Stokes (RANS) model, the turbulent viscosity of the liquid \(\mu_{ij}\) is given by:

\[
\mu_{ij} = C_{\mu} \cdot \rho_i \cdot \frac{k_{ij}^2}{\epsilon_i} \quad \text{............ (6)}
\]

where \(C_{\mu}\) is a constant equal to 0.09, \(k_i\) is the turbulent kinetic energy of the liquid and \(\epsilon_i\) is the dissipation rate. For the dispersed phase (bubbles), the turbulent quantities are provided as a function of the results of the continuous phase and the bubble Stokes number. However, the bubble wake produces turbulent energy that is not basically taken into account in the standard \(k-\epsilon\) model. Two approaches are proposed to account for the turbulence induced by the bubble motion (Bubble-Induced Turbulence, BIT). The first one modifies the \(k-\epsilon\) model through two source terms, \(S_i\) and \(S_{\epsilon}\), for each of the two transport equations (Simonin and Viollet\(^{19}\)). The second approach (Sato and Sekogushi\(^{20}\)), which has been chosen in this work, adds a third contribution to the liquid effective viscosity:

\[
\mu_{eff,i} = \mu_{ij} + \mu_{ij} + \mu_{BTR} \quad \text{with} \quad \mu_{BTR} \quad \text{............ (7)}
\]

\[
\mu_{BTR} = 0.6d_b \cdot \rho_i \cdot \rho_i \cdot |u_g - u_l| \quad \text{............. (8)}
\]

where \(\mu_{ij}\) is the molecular liquid dynamic viscosity and \(\mu_{BTR}\) is the contribution due to turbulence induced by bubbles.

At the bubble size-length scale, turbulent agitation of the liquid produced by the bubble motion acts on the plume as a dispersion force directed towards regions with low gas hold-up, as shown schematically in Fig. 2.

Following Davidson,\(^{21}\) the turbulent dispersion force is proportional to the fluid turbulent diffusivity \(D_k\), and the gradient of gas retention rate \(\nabla \alpha_g\):

\[
F_{TD} = \frac{3}{4} \frac{C_D}{d_b} \rho_l \left| u_g - u_l \right| \nabla \alpha_g \quad \text{............ (9)}
\]

The turbulent diffusivity must be calculated to solve Eq. (9). A first guess was to identify it with the turbulent kinematic viscosity of the continuous phase \(\nu_l\). However, the simulation results have shown that the plume dispersion is then overrated. Strictly speaking, the turbulent diffusivity \(D_k\) is equal to the fluid-particle turbulent diffusivity \(\nu'_{lg}^*\); Simonin and Viollet\(^{19}\) have demonstrated that the simplest form is:

\[
D_k = \langle u'_l u'_g \rangle T_{lg} \quad \text{............... (10)}
\]

where \(\langle u'_l u'_g \rangle\) is the covariance between the velocity fluctuations of bubble and liquid phases and \(T_{lg}\) is the integral time scale of the fluid seen by the bubbles. The active participation of Oesterle\(^{22}\) in the CIREM program led to an estimation of these two quantities:

\[T_{lg} = T_L \left( 1 + 1.9 \frac{U_g^2}{2k_L} \right)^{-1/2}\]

where \(T_L\) can be estimated by:

\[
T_L \cong \frac{\nu}{2k_L} \cong \frac{3C_{\mu}k}{2\epsilon}
\]

The fluid-particle velocity covariance, is predicted by the Chen theory:

\[
\langle u'_l u'_g \rangle = \langle u'_l^2 \rangle \frac{1 + bSt}{1 + St}
\]

where \(b = 3\rho_l (2\rho_p + \rho_l)\) is the added mass parameter (its value is close to 3 for the bubbles) and \(St\) is the bubble Stokes number based on \(T_{lg}\)

\[
St = \frac{\tau_p}{T_{lg}}
\]

For a bubble \((\rho_b << \rho_l)\), the relaxation time is expressed as:

\[
\tau_p = \frac{d_b}{4C_{Dp}U_g} \quad \text{therefore} \quad \tau_p = \frac{d_b}{4U_g} \quad \text{with} \quad C_{Dp} = 8/3
\]

3.1.4. Boundary Conditions

At the inlet (injector) and outlet (top surface) of the ladle, we have implemented source terms in Eqs. (1) and (2) for the gas phase with the aim of modelling gas injection and degassing. On the surface of the bath, a slip condition was used for the liquid phase and Neumann conditions (zero flux) were applied to transport equations of \(k\) and \(\epsilon\). The no-slip condition was selected for the other domain boundaries for both phases, while wall functions were applied on all
solid wall boundaries.

3.2. Modelling of Inclusion Behaviour

The behaviour of the inclusion population, defined by a distribution function of particle size \( N_i \) (the number of inclusions of class \( i \) per \( m^3 \) of liquid steel), is described by the population balance equation (PBE). Eq. (11) represents the macroscopic transport phenomena of inclusions (left member), and mesoscopic phenomena such as bubble-inclusion (floatation \( Z_{bi} \)) and inclusion-inclusion (aggregation \( B_i–D_i \)) interactions:

\[
\frac{\partial \alpha_i N_i}{\partial t} + \text{div}(\alpha_i \mathbf{u}_i N_i) = \alpha_i (B_i - D_i) - Z_{bi} - S_i \quad \ldots \ldots \ldots (11)
\]

In Eq. (11), \( S_i \) is the inclusion gravity separation term. The transient solution to this equation can be obtained by separating the transport and collision operators.\(^{23,27,28}\) In the first part of the time step, the transport equation of the quantity \( N_i \) is solved using the Finite Volume Method:

\[
\frac{\partial \alpha_i N_i}{\partial t} + \text{div}(\alpha_i \mathbf{u}_i N_i) = 0 \quad \ldots \ldots \ldots (12)
\]

In the second part of the time step, the population balance (Eq. (13)) is solved in each control volume applying the cell average technique\(^{24}\) which is a variant of the fixed pivot method of Kumar and Ramkrishna:\(^{25}\)

\[
\frac{\partial \alpha_i N_i}{\partial t} = \alpha_i (B_i - D_i) - Z_{bi} - S_i \quad \ldots \ldots \ldots (13)
\]

3.2.1. Aggregation

The term \( (B_i - D_i) \) is expressed as in the original formula of Smoluchowski, where \( \beta_i \) that appears in the formula is the so-called aggregation kernel. For the hydrodynamic conditions prevailing in the liquid metal ladle, the aggregation is mainly carried out by turbulence. The aggregation kernel proposed by Zaichik et al.\(^{26}\) has been chosen for this work. The reader will find further information on the validity of the aggregation kernel and its expression in.\(^{27}\)

3.2.2. Floatation

\( Z_{bi} \) is expressed by the following relationship:

\[
Z_{bi} = E_c \alpha_i \beta_{bi} N_b N_i \quad \ldots \ldots \ldots \ldots (14)
\]

where \( E_c \) is the collision efficiency and \( N_b \) is the numerical density of bubbles. The floatation kernel \( \beta_{bi} \) is expressed as the sum of two terms, a deterministic \( \beta_{det} \) kernel (bubble-inclusion slipping velocity) and a stochastic \( \beta_{turb,i} \) kernel (turbulent agitation of particles).

The expression for the deterministic component of the floatation kernel is given by the volume of fluid swept by the bubble per unit time:

\[
\beta_{det} = \frac{\pi d_{bi}^2 U_{bl}}{4} \quad \ldots \ldots \ldots \ldots (15)
\]

where \( U_{bl} \) is the average sliding liquid-bubble velocity.

The stochastic component can be calculated in the same way as the process of particle-particle collisions. Thus, we selected the Saffman and Turner\(^{20}\) model, used by several authors (Koh and Schwarz,\(^{29}\) Kostoglou\(^{30}\)). The application of this model (Eq. (16)) assumes that inclusions have a low inertia and a size smaller than the Kolmogorov scale:

\[
\beta_{turb,i} = \frac{8\pi}{15} \left( \frac{d_{bi} + d_{mi}}{2} \right)^3 \left[ \frac{E_{i}}{v_t} \right]^{1/2} \quad \ldots \ldots \ldots (16)
\]

where \( d_{mi} \) is the particle diameter representative of the i class and \( v_t \) is the kinematic viscosity of the liquid. The extension of collision efficiency models in literature to the case of bubble with the shape of a spherical cap (in the bubbles plume) has to be carefully treated. To calculate \( E_c \), associated with this morphology, we used an adaptation (Söder et al.\(^{31}\)) of the efficiency model of Sutherland,\(^{32}\) obtained by calculating the critical streamline around a spherical bubble in the hypothesis of a potential flow. The modified expression is given by:

\[
E_c = 1.7 \left( \frac{d_{bi}}{d_b} \right) \quad \ldots \ldots \ldots (17)
\]

3.2.3. Separation Induced by Gravity

The local velocity of oxide inclusions is decomposed into a sum of a local fluid velocity and a Stokes velocity (inclusions float naturally to the top since \( \rho_i > 0, \rho = \rho_l \)). Following this decomposition, the source term \( S_i \) for the transport equation is:

\[
S_i = div(\alpha_i \mathbf{u}_i N_i) \quad \ldots \ldots \ldots \ldots (18)
\]

where \( \mathbf{u}_i \) is the vertical Stokes velocity in the case of small inclusions whose particle Reynolds number is lower than 1:

\[
u_i = \frac{d_{mi}^2 (\rho_l - \rho_i) g}{18 \mu_i} \quad \ldots \ldots \ldots (19)
\]

3.2.4. Entrapment at the Ladle Free Surface

In order to model the inclusion entrapment at the liquid metal/slag interface, we adopted the approach proposed by Xayasen\(^{33}\) based on a deposition law developed initially by Wood.\(^{34}\) The deposition rate is applied on the adjacent cells of the interface using an out-flow density boundary condition of the population balance Eq. (13):

\[
\phi_i = -\alpha_i u_{d,i} N_i \quad \ldots \ldots \ldots (19)
\]

The flow \( \phi_i \) takes into account the adimensional inclusion deposition velocity \( u_{d,i} \) obtained by the empirical expression of Wood:

\[
u_{d,i} = \frac{u_{d,i}}{u} = \frac{0.0575 C^{1.2} + 4.5 \times 10^{-4} r_{p}^{2/3}}{\nu_{p}} \quad \ldots \ldots \ldots (20)
\]

where \( u_{d,i} \) is the adimensional inclusion deposition velocity for the i-class particles, \( \nu \) is the shear velocity of the liquid, \( \nu_{p} \) is the Schmidt number and \( r_{p}^{2/3} \) is the dimensionless relaxation time of the inclusion.

The first term on the right side of Eq. (20) represents the Brownian effects (involving micro-inclusions of the order of one micrometer) and the second represents the inertial effects (more important for macro-inclusions).

4. Numerical Procedure

The solution to the system of equations is based on the Fluent CFD code V12.1, where a large number of user defined functions (UDF) has been incorporated in order to take into account all the features of our model. In particular,
while the transport equation of a passive scalar \( N_t \) (Eq. (12)) is solved by default with the code, Eq. (13) is calculated at the end of each time step in a specifically developed module. The simulations were performed on a 3D geometry with a 30,000 cells mesh. The time step was chosen according to the Courant number (\( Co < 1 \)) and the convergence criterion on residuals was set to \( 10^{-6} \). An implicit method and a second-order QUICK scheme were chosen for solving the transport Eq. (12), while the solution of PBE (13) was obtained by a discrete class method (CM), described in detail in reference24 and successfully compared with the quadrature method of moments (QMOM) in reference.27

5. Results and Discussion

The simulations reported in this section refer to the bubbling of argon in liquid Wood’s alloy, which offers an element of validation for the hydrodynamic part of our model. Xie et al. studied experimentally10 the hydrodynamics in an Oeters’ ladle (Fig. 3) equipped with sensors providing access (at different locations) to: the bubble diameter, the gas retention, each phase velocity and transported powers, associated with the average and turbulent kinetic energy. The Wood’s alloy Sn–Bi–Pb–Cd is liquid at low temperature (70°C) and has thermo-physical properties closer to those of liquid steel than water. The Oeters’ ladle operated with an argon gas flow rate equal to 0.72 N.m\(^3\).h\(^{-1}\) and the bubble diameter at the gas injection is 20 mm.

5.1. Hydrodynamic Simulation

As an example, Fig. 4 presents the computed gas retention and liquid velocity in a central plane of the Oeters’ ladle. Figure 4(a) shows the shape of the bubble plume with a strong aeration of the bath. Much higher values of retention rates are obtained, as compared to predictions in industrial steel ladles. The liquid metal flow associated with argon behaviour (Fig. 4(b)) is the place for strong axi-symmetric recirculation. The maximal velocity in the liquid alloy is reached at the centre of the plume and near the surface of the bath and equal 0, 29 m/s.

Figures 5(a) and 5(b) give valuable comparison between measurements and predicted values and show a satisfactory prediction (orders of magnitude of gas-retention and liquid velocities are in agreement), but with an overestimation of the plume width, induced by the turbulent dispersion force. The estimation of turbulent diffusivity \( D_t \) plays a major role here, and the expression (10) points out the turbulence mod-
ulation of calcium aluminate inclusions. This distribution matches relatively well with those analysed in industrial ladle since one kilogram of metal contains 5 \(10^6\) inclusions smaller than 20 \(\mu m\) but only 5.7 \(10^4\) larger than 20 \(\mu m\). Unfortunately the log-normal law cut off the distribution for the inclusions larger than 30 \(\mu m\) which does not fit with accurate cleanliness measurements detecting rare (but existing) large inclusions (>50 \(\mu m\)). The distribution is plotted in Fig. 6 where the inclusion population is rendered discretely into twenty different sized classes.

Figure 7(a) compares the initial particle distribution (black) with the two calculated after 300 s (green) and 600 s (red) of treatment. During the gradual evolution of the distribution, larger size particles appear due to the agglomeration of small size particles (\(d_p<20\ \mu m\)) of which the quantity strongly decreases. Otherwise the number of 23 \(\mu m\) sized inclusion remains quite stable during the first 300 s meaning that the relatively small increase of the inclusion quantity due to aggregation is balanced by the quantity of inclusion removed (flotation …). As shown in Fig. 7(b), the variation of the Sauter diameter \(d_{32}\) over time confirms the evolution of the distribution to larger sizes during the first 400 s of the process and then levels off due to the removal of particles larger than 23 \(\mu m\). One way to assess the importance of the aggregation phenomenon is to calculate the index \(I_{ag}\) on the whole volume of the ladle, defined as follows:

\[
I_{ag} = \frac{N_{tot}(t = 0) - N_{tot}(t)}{N_{tot}(t = 0)} \quad \ldots \ldots \ldots \ldots (21)
\]

After 600 s the aggregation index reaches 0.89 indicating a phenomenon already advanced at the end of the duration of treatment.

The numerical simulation allows us to compare the relative role of the different removal mechanisms on the inclusion population and the frequencies of the aggregation, flotation, settling and capture on the free surface have been reported in Fig. 8 (at time equal to 300 s). The sign (–) or (+) indicates either the numerical density of a given class decreasing or increasing respectively following the aggregation process. Thus the aggregation frequency \(F_A\) is calculated as:

\[
F_A = \int (B_i - D_i) dV \quad \ldots \ldots \ldots \ldots (22)
\]

Another interesting thought suggested by the numerical results concerns the global rate of inclusion removal corresponding to a deoxidation rate (assuming a constant nature of inclusions and dissolved oxygen content).
The first statement proves that the deoxidation kinetics does not fit with a first order law written as:

\[
\frac{dC_O}{dt} = -K_OC_O \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (23)
\]

where \(C_O\) expresses the TO.

Indeed the variation with time of inclusion weight content in a logarithmic scale (Fig. 9(a)) is not linear at all, as it was confirmed by the calculation of \(K_O\), which is not constant. It can be readily explained by the major role played by the aggregation process on the psd which is a quadratic mechanism. Finally the value of \(K_O\) depends on the psd itself.

A second statement relates the deoxidation rate predicted by our numerical code and the values referenced in the literature. Zhang and Thomas\(^{35}\) have plotted industrial efficiencies in a diagram for different stirring practices (Fig. 9(b)). Even if the relevance of the first order kinetics can be doubtful (for the reason mentioned above) this diagram brings an order of magnitude of the deoxidation rate as a function of the stirring power. We notice that the range of variation of the calculated deoxidation rate matches well with the literature data.

The total number density map (\(N_{\text{tot}}\) in particles/m\(^3\)) of Fig. 10 shows certain non-homogeneity in the ladle at a specific instant of time during the treatment. This result implies that the characteristic times of aggregation mechanisms, flotation and entrainment cannot be regarded as infinitely large in comparison with the transport characteristic time. Thus, there is a decrease of \(N_{\text{tot}}\) in the area of the plume and near the free surface in regions where these mechanisms are acti-
vated by turbulence and high retention rates. This fact alone justifies the choice of 3D modeling.

6. Conclusion

A mathematical model of inclusion behaviour in a gas stirring ladle has been built up step by step. First the turbulent flow is simulated using the Euler-Euler method and takes into account all the interaction forces between the two phases (gas bubbles and liquid steel), i.e. drag, lift, added mass and turbulent dispersion. A satisfactory validation is obtained with the prediction of the gas-liquid hydrodynamics of the experimental Oeters’ ladle.10 Second the numerical model handles both agglomeration and removal mechanisms (flocculation, settling, free surface entrainment) together with the convective transport of inclusions into the melt. The coupling of the convective transport equation and the PBE is achieved using a splitting technique. The discrete class method with the cell average feature was adopted to solve the PBE and was implemented into the CFD code.

This model is applied to the Oeters’ ladle with a realistic population of inclusions where the size initially ranges between 2 and 36 microns. The results emphasize that the aggregation mechanism plays a major role by translating the particle size distribution (psd) towards the large size and therefore leading to an increase of the Sauter diameter. The removal mechanisms are mainly flotation and gravity separation of which the efficiency increases with the inclusion size. In conclusion the inclusion removal in the gas stirring ladle can be described as the aggregation of small particle sizes to agglomerates which are finally removed by flotation or settling. As a consequence the simulations pointed out that the deoxidation rate is no longer a first order law since the aggregation is a quadratic mechanism.

However, the mathematical model remains to be improved if we wish to have a more accurate simulation of the complex behaviour of the oxide inclusions. Among the improvements, the thermo-chemical equilibrium associated with the nucleation-growing kinetics and a more realistic description of the top slag layer most likely represents the greatest issues. In addition, the important complexity of the ladle system (three spatial dimensions, one internal coordinate and the temporal dimension) requires a large computing effort and makes the numerical code quite inapplicable for industrial engineering, however future improvements in CPU could change this. In this context we are involved in the development of a 0D model assuming a perfect mixing of the reactor and comparisons between 0D and 3D codes will shortly be published.

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REFERENCES