Note

Short Contribution to the Mathematical Modeling of Coagulation Effect on Entrapped Inclusion Concentration in Continuously Cast Steel

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The quality improvement of products in the continuous casting (CC) of steel requires more and more to remove the alumina inclusions from the cast strands. The removal of larger Al_2O_3 -particles from the surface layer of the cast strand, where their presence can generate cracks and slivers in the subsequent processes, can be achieved during electromagnetic mould stirring (EMS) by the “washing effect”, *i.e.* the non-metallic inclusions are washed away from the solidifying shell by the horizontally stirred molten steel.^{1,2)}

The content of smaller particles can be reduced in stirred turbulent flows by their more frequent collisions and coalescences,³⁾ because thus will appear larger inclusions with greater rising velocities and removal rates. Therefore, the knowledge and simulation of the particle agglomeration in the CC with EMS become important.

The concentration, *i.e.* the number of alumina particles per unit volume of steel, can be determined for m spherical particle types with the selected diameters d_i and volumes V_i , by solving the transport equations^{4–6)}

$$\text{div}(\mathbf{v}_{pi} c_i - v_t \text{grad } c_i) = s_i, \quad i = 1, 2, \dots, m \dots\dots\dots (1)$$

where c_i and $\mathbf{v}_{pi}$ denote the concentration and the velocity of the particles of i -th type, v_t is the turbulent viscosity and $s_i = G_i + D_i$ represents a source term, composed of a generation term $G_i > 0$ and a disappearance term $D_i < 0$.

Usually, the diameters of the new particles generated by collision and coagulation are approximated by the selected diameters,^{4,5)} when the particle mass conservation is no more satisfied. To satisfy this condition Tozawa *et al.*⁶⁾ calculated the concentrations of alumina clusters considering every size from a primary constituent particle to the largest cluster, but this made necessary to solve a relatively great number of coupled differential equations. To save computational time, Ishii *et al.*⁷⁾ considered 1 025 particle sizes and solved the Eqs. (1) only for 13 selected sizes. For the rest of sizes the concentrations were calculated applying linear interpolations, by which the conservation of the particle mass is not strictly satisfied. Nakaoka *et al.*⁸⁾ introduced correction factors of the particle number density to keep the particle-volume conserved, but thus, the number of new particles is no more equal, for all collision combinations, to the half of the coagulating particle number. Using for the inclusions a continuously variable radius and exponential distributions of the number density, Lei *et al.*⁹⁾ developed a model with 2 conservation equations, by which a character-

istic inclusion concentration is calculated. The concentration of particles with a certain diameter cannot be obtained by this model and therefore, *e.g.* the washing effect, for which the boundary conditions depend on the particles diameter,¹⁰⁾ cannot be studied.

In this paper the particle concentrations are calculated using source terms, by which both the volume conservation and the condition, that the particle number is halved by coalescence, are fulfilled.

If by collision between n particles of j -th type and n particles of k -th type result particles, whose volumes $V_{jk} = V_j + V_k$ satisfy the inequality $V_i < V_{jk} < V_{i+1}$, then an approximation possibility is to consider the n new particles as to be composed of n_i particles of i -th type and n_{i+1} particles of type $i+1$, with

$$n_i = Nn = \frac{V_{i+1} - V_{jk}}{V_{i+1} - V_i} n, \quad n_{i+1} = Mn = \frac{V_{jk} - V_i}{V_{i+1} - V_i} n \dots (2)$$

Thus, both the volume conservation $n_i V_i + n_{i+1} V_{i+1} = n V_j + n V_k$ and the condition, that by coalescence the number $n_i + n_{i+1} = n$ of the new particles is equal to the half of the number $2n$ of the colliding particles, are satisfied.

For simplicity the diameters d_i of the m particle types are set so that $2V_i \leq V_{i+1}$; then particles of i -th type can appear by collision between particles of types $i-1$ and $j=1, 2, \dots, i-1$ and also of types i and $j=1, 2, \dots, i$, respectively. Consequently, the generation term will be determined as the sum $G_i = G_{iM} + G_{iN}$, with¹¹⁾

$$G_{iM} = \sum_{j=1}^{i-1} M_{ij} \beta_{i-1j} c_{i-1} c_j, \quad G_{iN} = \sum_{j=1}^i N_{ij} \beta_{ij} c_i c_j \dots\dots (3)$$

where β_{ij} denotes the turbulent collision rate^{3–5,8,9)} and according to the factors M and N in the Eqs. (2)

$$M_{ij} = \frac{V_{i-1j} - V_{i-1}}{V_i - V_{i-1}}, \quad N_{ij} = \frac{V_{i+1} - V_{ij}}{V_{i+1} - V_i}, \quad V_{ij} = V_i + V_j \dots (4)$$

By neglecting the coagulation of the particles of m -th type, will result the following equations of the source terms¹¹⁾

$$s_1 = G_{1N} + S_1, \quad s_i = G_{iM} + G_{iN} + S_i, \\ i = 2, 3, \dots, m-1, \quad s_m = G_{mM} \dots\dots\dots (5)$$

in which the disappearance term is calculated by⁸⁾

$$S_i = - \sum_{j=1}^{m-1} (1 + \delta_{ij}) \beta_{ij} c_i c_j \dots\dots\dots (6)$$

δ_{ij} being the Kronecker symbol.

Volume concentration equations are obtained by multiplication of each Eq. (1) by the corresponding volume V_i . For the coagulation among the particles of i -th and j -th types, with $j \leq i$, in the volume concentration equations i and $i+1$ appear two generation terms, whose sum

$$V_i N_{ij} \beta_{ij} c_i c_j + V_{i+1} M_{i+1j} \beta_{ij} c_i c_j = V_{ij} \beta_{ij} c_i c_j \dots\dots\dots (7)$$

results, for $j < i$, equal to the sum with opposite sign of the corresponding disappearance terms contained in the equations i and j

$$-V_i \beta_{ij} c_i c_j - V_j \beta_{ji} c_j c_i = -V_{ij} \beta_{ij} c_i c_j \dots \dots \dots (8)$$

For $i=j$, the sum (7) is equal to the corresponding disappearance term with opposite sign from the equation i

$$-V_i 2\beta_{ii} c_i c_i = -V_{ii} \beta_{ii} c_i c_i \dots \dots \dots (9)$$

Therefore, at summation of the m volume concentration equations, the sum of all generation and disappearance terms vanishes, by which the particle volume conservation is satisfied.¹¹⁾

Further the concentration Eqs. (1) will be considered. For the coagulation of the same particle types i and j , the sum of the corresponding generation terms appearing in the concentration equations i and $i+1$

$$N_{ij} \beta_{ij} c_i c_j + M_{i+1j} \beta_{ij} c_i c_j = \beta_{ij} c_i c_j \dots \dots \dots (10)$$

is equal, for $j < i$, to the half of the sum with opposite sign of the corresponding disappearance terms contained in the equations i and j

$$-\beta_{ij} c_i c_j - \beta_{ji} c_j c_i = -2\beta_{ij} c_i c_j \dots \dots \dots (11)$$

For $i=j$, the sum (10) is also equal to the half of the corresponding disappearance term $-2\beta_{ii} c_i c_i$, with opposite sign, from the concentration equation i . These half-conservations correspond to the condition, that by coagulation appear new particles, whose number is equal to the half of the colliding particle number.¹¹⁾

After numerical solving of Eqs. (1) with the source terms (5), the removal rate can be calculated, which is defined as the ratio of the particle volume flux absorbed by the slag at the interface *Int* (Fig. 1) to the incoming flux through the outlet surface *S* of the submerged entry nozzle (SEN).

Using the finite difference method, the concentrations of particles with diameters of 30, 60, 90, 120, 160 and 210 μm , respectively, were determined in a continuously cast round strand of radius $R=12$ cm (Fig. 1), in which the rotational EMS is performed with a near-wall velocity of about 40 cm/s.^{1,2,10)} The characteristics of the calculated configuration and the boundary conditions used for the concentration computation are the same as given in the Ref. 10).

At the surface *S* (Fig. 1), the incoming concentrations were appointed by $c_i = C \exp(-\alpha d_i/2)$ with the constants $C = 1.873 \cdot 10^{13} \text{ m}^{-3}$ and $\alpha = 2.9 \cdot 10^5 \text{ m}^{-1}$, which were obtained by means of the 12 values of the concentration listed in Ref. 5). The turbulent collision rates β_{ij} were calculated using for the coagulation coefficient the experimentally derived value of 0.18.¹²⁾ In applying the Gauss-Seidel procedure, a considerable convergence improvement results using for the determination of the diagonal elements of the coefficient matrix also the factors $F_i > 0$ from the source term differences $G_{iN} - S_i = -F_i c_i$.¹¹⁾

The calculated removal rate 0.3 is much greater than the value 0.0115 computed with $s_i = 0$, i.e. by neglecting the particle collisions and coalescences.¹¹⁾ The removal rate has a relatively small value because even after the coagulations, the number of smaller particles with smaller rising velocities and removal rates remains preponderant.

The concentration fields were calculated in the strand down to a depth of $z = -4$ m.¹⁰⁾ The distributions of the final concentration c_s in the solidified shell were determined at $z = -4$ m, where the shell thickness is equal to 5 cm¹⁰⁾ and it

Fig. 1. Configuration of the CC process with EMS (schematic): 1, SEN; 2, mould; 3, molten steel; 4, solidified shell; 5, liquid slag; 6, mould powder and sintered flux; 7, magnetic core of the stirring inductor.

Fig. 2. Radial distribution of the final concentration c_s (number of particles in 1 cm³ of steel), calculated for alumina particles of 160 μm diameter in a round strand of 12 cm radius, continuously cast with EMS.¹¹⁾

follows, that the concentrations c_s were calculated for $7 \text{ cm} < r < 12 \text{ cm}$ (Fig. 2). Due to the washing effect, the final concentration of the particles with the diameter of 160 μm results advantageously equal to zero in the surface layer with the thickness of 1.3 cm, i.e. for $10.7 < r < 12 \text{ cm}$ in Fig. 2,^{10,11)} which corresponds to the industrial measured absence of greater particles in the subsurface layer of the cast slabs with EMS.^{1,2)}

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