The Washing Effect in Electromagnetic Rotational Stirrers for Continuous Casting

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During electromagnetic mould stirring (EMS) in continuous casting (CC) of steel the “washing effect” of the alumina particles is known, i.e. the horizontal stirred flow of the molten steel can wash away the non-metallic inclusions from the solidifying shell.1–5 Thus the washed particles of diameters greater than 100 μm are removed from the surface layer of the cast strand,3,4 where their presence can generate cracks and slivers in the following processes.5 Because of this advantageous effect the EMS was introduced at CC of slabs by the Nippon Steel Corporation.3,4

The conventional EMS in round strands, i.e. using a rotational two-pole magnetic field, cannot be applied in the CC under mould powder because the stirring causes the disadvantageous entrapment of the casting flux in the melt and a rapid erosion of the submerged entry nozzle (SEN).6 A possibility of rotational EMS could be the “near-wall” stirring,7 i.e. using two opposite rotational magnetic fields with different pole pair numbers. By this two-field method only the outer layers are stirred while the inner part of the strand is not agitated and thus the mentioned disadvantages practically no more appear.7

In this paper the usage of the near-wall EMS in CC of a round strand (Fig. 1) with the characteristics given in Table 1 is studied. After a short presentation of the electromagnetic and flow fields calculation8,9 the concentration distribution of alumina particles is computed using a boundary condition10 which takes the washing effect into consideration. All calculations were made in cylindrical coordinates (r, φ, z) applying the finite difference method for a 26×76 grid in the directions r and z, extended in the SEN (Fig. 1) up to a height of z=120 mm and in the strand down to a depth of z=−4 m.9

The density components $J_r$, $J_φ$, $J_z$ of the electric current in the steel strand were numerically determined with the law of electromagnetic induction9 using for the magnetic inductions of the two rotational fields with the pole pair numbers $p_i$ (i=1,2) the following expressions in the domain $−b≤z≤0$ (Fig. 1):

$$ B_{ri} = B_{qi} = B_0 \left( \frac{r}{R} \right)^{i-1}, \quad i = 1, 2 \quad \ldots (1) $$

where $B_{ri}$ represent the r.m.s. value at the strand surface $r=R$.

The components of the electromagnetic force density are obtained by the superposition30 of the force densities9

$$ f_r = f_{r1} + f_{r2}, \quad f_φ = f_{φ1} - f_{φ2} \quad \ldots (2) $$

of the force densities9

![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.](image)

| Table 1. Characteristics of the calculated configuration (Fig. 1).9 |
|------------------|------------------|
| **configuration of the CC process** |                    |
| radius of the cast strand | $R = 120$ mm |
| radii, submergence depth of the SEN | $r_1 = 17.5$ mm, $r_e = 42.5$ mm, $d = 88.5$ mm |
| height of the liquid slag layer | $h = 10$ mm |
| casting speed, solidification constant | $v_c = 1$ m/min, $K = 25$ mm/min$^{0.3}$ |
| characteristics of the molten steel | $σ = 0.71×10^5$ S/m, $ρ_s = 7200$ kg/m$^3$,  $\nu = 0.83×10^{-6}$ m$^2$/s |
| densities of the liquid slag, of the alumina particles(5) | $2500$ kg/m$^3$, $ρ_α = 2700$ kg/m$^3$ |
| **inductor for the near-wall EMS** |                    |
| pole pair numbers, feeding frequencies of the two three-phase windings | $p_1 = 4, p_2 = 1$, $f_1 = 8$ Hz, $f_2 = 2$ Hz |
| r.m.s. values of the magnetic inductions produced at $r=R$ by the two windings | $B_{01} = 47.4$ mT, $B_{02} = 26.2$ mT |
| height of the magnetic core | $b = 200$ mm |
\[
f_i = -\frac{s \omega_i \sigma u_i}{2 \rho_i (p_i + 1)} \cdot r^2 J \rho_i B_{ai}^2, \quad f_{qi} = J \rho_i B_{ai}^2, \quad i = 1, 2 \quad \ldots (3)
\]

\( s, \omega_i = 2 \pi f_i \) and \( \sigma \) denoting the local slip, the supply angular frequency and the electrical conductivity.

The values of \( f_i \) and \( f_2 \) in Table 1 are the optimum feeding frequencies of the two inductor windings,\(^9\) for which the greatest stirring force densities \( f_{qi} \) result when the inductor is placed inside a copper mould with the wall thickness of \( t = 2 \text{ cm} \)\(^{11}\) (Fig. 1).

The turbulent flow of the molten steel was calculated using an anisotropic version of the \( k-\varepsilon \) turbulence model developed for rotational flows\(^9\) on the basis of the results obtained with the algebraic Reynolds stress model.\(^{12,13}\)

This version uses the equations of the usual \( k-\varepsilon \) model in which only the shear stress \( \tau_{\varepsilon} \) and the production term \( P_{\varepsilon} \) depending on \( r \) and the azimuthal velocity \( v_\phi \) are modified:\(^8\)

\[
\tau_{\varepsilon} = \rho_\varepsilon (v + v_\varepsilon) D, \quad P_{\varepsilon} = v_\varepsilon D^2, \quad D = r \frac{\partial}{\partial r} \left( \frac{v_\phi}{r} \right)
\]

\[..........................(4)\]

where \( \rho_\varepsilon \) and \( v \) are the density and the laminar viscosity of the molten steel and \( v_\varepsilon \) represents a reduced turbulent viscosity in the flow-mechanically stable layers, \( i.e. \) with positive derivative in \( r \)-direction of the angular momentum \( v_\varepsilon r \).\(^{8,9}\)

\[
v_\varepsilon = \frac{v_1}{1 + F}, \quad v_1 = c_\mu \frac{k^2}{\varepsilon}, \quad F = \frac{8}{\varepsilon} \left( \frac{a k}{H_{11005}} \right)^2 \frac{\partial}{\partial r} (v_\phi r)
\]

\[..........................(5)\]

\( k \) and \( \varepsilon \) being the turbulence kinetic energy and the rate of dissipation and \( c_\mu = 0.09, \alpha = 0.2 \).

The laminar flow of the upper liquid slag (Fig. 1) was calculated using a viscosity depending on the temperature,\(^{14}\) whose distribution in the slag layer was also numerically computed.\(^9\)

The r.m.s. values \( B_{01} \) and \( B_{02} \) in Table 1 were chosen so that the stirring forces drive a near-wall flow with the optimum velocity of 40 cm/s (Fig. 2) which was experimentally determined in the CC of slabs with EMS in order to improve the surface quality by the washing effect of the greater non-metallic inclusions.\(^3,5\)

The concentration \( c \) of alumina particles was computed by numerical solution of the equation\(^{5,16}\)

\[
\text{div} \, q = 0, \quad q = \nabla \rho_\varepsilon - \nabla \text{grad} \, c \quad \ldots \ldots (6)
\]

where the velocity \( v_\phi \) of particles with the diameter \( d_\phi \) was calculated by the velocity \( v \) of the molten steel and the rising velocity according to Stoke's law.\(^9\)

\[
v_\rho = v + \left( \frac{\rho_\rho - \rho_\varepsilon}{18 \rho_\varepsilon} \right) \frac{d_\phi^2}{2} \left( -\frac{v^2}{r}, u, + g \varepsilon \right) \quad \ldots \ldots (7)
\]

In Eq. (7) \( \rho_\rho \) is the particle density, \( u \), and \( u \) represent the unit vectors in the directions \( r \) and \( z \), the term containing \( v_\phi^2 \) considers the particle transport to the strand middle due to the centrifugal forces and \( \vartheta = 9.81 \text{ m/s}^2 \).

The incoming concentration in the SEN was normalized to unity and the washing effect was considered by introducing a supplementary factor \( C_w \) in the expression of the boundary concentration flux density normal to the solidifying shell wall.\(^{13,9}\)

\[
q_w = C_w \frac{c_w}{v_\varepsilon} \quad \ldots \ldots \ldots (8)
\]

In Eq. (8) \( c_w \) terms the near-wall concentration, \( v_\varepsilon \) the growth rate of the shell thickness \( \delta \) (Fig. 1)\(^{16}\):

\[
\delta = K \sqrt{\frac{v_\varepsilon}{v_\varepsilon}}, \quad v_\varepsilon = \frac{K}{2} \sqrt{\frac{v_\varepsilon}{v_\varepsilon}} \quad \ldots \ldots (9)
\]

\( K \) and \( v_\varepsilon \) denoting the solidification constant and the casting speed given in Table 1.

The numerical modelings of the particles motion indicate that the washing effect is produced by the viscous drag and the Saffman forces acting on the particles near the solidified shell.\(^1,17\) The theoretical study\(^{11} \) as well as the experiments with particles in a water model\(^{16,19} \) and the industrial concentration measurements\(^3,5\) show that the particles moving in a stirred fluid are impeded by the mentioned forces to stop on the shell surface and thus to be captured by the growing shell if their diameters are greater than a critical diameter which depends on the fluid velocity. Using these results the following expressions were obtained for the factor \( C_w \) in Eq. (8)\(^{10}\):

\[
C_w = 1 \quad \text{if} \quad d_\rho^* = \frac{U_\rho}{\vartheta} < 3.1, \quad C_w = 0 \quad \text{if} \quad d_\rho^* \geq 3.1
\]

\[..........................(10)\]

where \( d_\rho^* \) and \( U_\rho \) are the normalized diameter and the wall shear stress velocity.

The radial distribution of the final concentration \( c_s \) in the solidified cast strand can be obtained by:
The concentration field of alumina particles with diameter $d_p=150 \mu m$ was calculated in the strand down to a depth of $z=4 m$\(^3\) and the final concentration $c_s$ was determined in the solidified shell at $z=4 m$, where the shell thickness is $d=5 cm$. Without EMS the calculated concentration is $c_s \neq 0$ up to the strand radius ($Fig. 3$), i.e. the particles appear disadvantageous also in the surface layer. With EMS $c_s=0$ in the surface layer with a thickness of 1.3 cm ($Fig. 3$). This corresponds to the industrial measured absence of particles with diameters greater than $100 \mu m$ in the subsurface layer with 1 cm thickness of the cast slabs with EMS.\(^3\)\(^{-5}\) Below the SEN outlet the particles are transported by the molten steel downwards and near the solidified shell upwards.\(^9\) Therefore the near-wall concentration $c_w$ is greater in the upper part of the strand and has at about $z=-0.5 m$ a maximum which yields the peaks at $r \approx 10.2 cm$ of the distributions represented in $Fig. 3$.

Because of their rising velocity the particles move upwards to the steel/slag interface, where they are caught by the liquid slag and removed from the cast strand. The removal rate $\beta$ is defined as the ratio of the particle flux absorbed by the slag to the incoming flux through the SEN.\(^{15,16}\) In CC with EMS the washed particles dispose of a longer time to rise to the slag layer and therefore the rate $\beta=0.45$ results advantageous greater than $\beta=0.35$ determined for the CC without EMS.

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