Control of Gas Bubbles and Slag Layer in a Ladle Furnace by Electromagnetic Stirring

The demands on flow control in the ladle vary from different functions and stages in a ladle refining cycle. With the development of metallurgical knowledge, some common points on the fluid control in the ladle have been set. Strong turbulence or mixing at the slag/steel interface is required to achieve good desulfurization results. A short mixing time in the bath melt can lead to quick chemical homogeneity. Mixing time is affected by flow pattern, ladle size, turbulence intensity, etc. A relatively calm flow is good for the inclusion flotation and avoiding re-oxidation, slag entrapment, etc.

Gas stirring and electromagnetic stirring (Figure 1) have been the two dominant stirring methods in a ladle furnace. The strong slag/metal reaction with a high gas flowrate is preferable for desulfurization. The bubble cleaning effect with a low gas flowrate has also been widely utilized to remove inclusions. An electromagnetic stirrer (hereafter EMS) can create an effective stirring in the melt while keeping the whole melt surface covered by the slag layer. As a result of this feature, the yield of alloy additions and steel cleanliness is higher with electromagnetic stirring. The strength of EMS can be accurately controlled, which leads to high reproducibility and operational flexibility. The stirring directions by EMS can also be changed between upward and downward stirring.

The combination of electromagnetic and gas stirring (hereafter EMGAS) provides the possibility to utilize the advantages of both methods and further improve the performance of a ladle furnace. The basic idea of EMGAS is to control the gas bubbles in the melt, slag/metal interface, melt mixing, etc., by means of the combined effect of EMS and gas stirring. The optimal porous plug positions in the ladle bottom relative to the electromagnetic stirrer and the running parameters of both gas and electromagnetic stirring are the two primary questions to be answered in this project. These questions can be answered only when the fluid-dynamic features and their metallurgical potentials are fully understood. The final targets of EMGAS are to be able to shorten the refining time in the ladle furnace and/or improve the steel cleanliness.

In this paper, the numerical model and the simulation results of EMGAS are presented and compared with the results of a water model. The new features of EMGAS regarding the gas plume, stirring energy, velocity, mixing time, etc., are introduced. The metallurgical potentials are discussed.

Process Modeling

Physical System — The ladle system simulated in this paper is shown in Figure 2. The ladle inner diameter is 2.85 m, the melt height is 2.80 m and the initial slag layer thickness is 0.10 m. Different positions of the porous plug have been studied.

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**Numerical Methods** — Fluent© is employed for the numerical modeling of the system. The modeling of the melt, slag and the gaseous atmosphere in the ladle top is conducted using the Volume of Fluid (VOF) approach. This formulation relies on the fact that the fluids are not interpenetrating. The fields for all variables and properties are shared by the phases and represent volume-averaged values, as long as the volume fraction of each phase is known at each location. The mathematical model of the VOF approach consists of the continuity equation for each phase, the momentum equations based on one velocity and pressure field. The turbulence of the flow system is modeled using the Reynolds stresses model, which accounts for six equations, one for each Reynolds stress component, and the turbulent dissipation equation.

**Electromagnetic Stirrer Forces** — The electromagnetic stirring forces are applied to the cell centers of the CFD grid. The forces prior to the CFD simulation have been calculated using a commercial software, assuming zero velocity in the steel phase. In order to compensate for this, the force component in the stirring direction is recalculated in Fluent according to:

$$ F_z = F_{0,z} \left( 1 - \frac{w}{2v \tau} \right) $$

(Eq. 1)

where

- $F_{0,z}$ = the vertical stirrer force component read from the prior calculations,
- $w$ = the steel-phase vertical velocity component in the melt,
- $v$ = the stirrer frequency and
- $\tau$ = is the pole pitch, i.e. the center-to-center distance between two magnetic poles.

**Bubble Jet Modeling** — The gas is modeled using the Lagrangian particle tracking method, where every individual bubble trajectory is calculated, and source terms are taken into account to properly represent the interaction between the bubbles and the continuous phases for the momentum and heat. In the present study, a mono-sized bubble distribution of 5-mm-diameter bubbles is considered. The bubble drag and added mass forces, as well as the bubbles’ hydrodynamic expansion, are taken into account. A further sensitivity study needs to be conducted in order to assess the impact of other forces such as the lift, which is ignored in the present work. For the drag coefficient, $C_D$, the model of Morsi and Alexander² is used; and for the bubbles turbulence, the Random Walk Model is applied. The bubble compression or expansion due to hydrodynamic pressure is modeled by adjusting the density and the volume of the bubble while maintaining constant bubble mass. The hydrostatic pressure on the bubble at the porous plug inlet is given by:

$$ \Delta P_{tot} = \rho_{melt} g \Delta h_{melt} + \rho_{slag} g \Delta h_{slag} $$

(Eq. 2)

The local pressure head at any point in the melt is calculated as:

$$ \Delta P_{local} = \Delta P_{tot} - \rho_{melt} g \Delta h_{local} $$

(Eq. 3)

The ideal gas assumption gives the local bubble diameter:

$$ V_{b,local} = \Delta P_{tot} V_{b,inlet} / \Delta P_{local} $$

(Eq. 4)
The bubble density change due to hydrostatic pressure is calculated by linear interpolation:

\[
\rho_{b,\text{local}} = \rho_{b,\text{inlet}} + \left(1 - \frac{\Delta z}{\Delta h_{\text{melt}}} \right) \left(\rho_{b,\text{inlet}} - \rho_{b,\text{atm}}\right)
\]  

(Eq. 5)

**Simulated Cases** — The case list of numerical simulations is shown in Table 1.

**Water Model** — The ladle furnace water model experimental setup consists of a cylindrical vessel of 1.5 m height and 1.0 m internal diameter, filled with water until 0.85 m. A flexible plug is positioned at the bottom of the tank. There are eight immersed pumps, four placed at the bottom to pump the liquid upward and four placed under the water free surface to pump the liquid downward. The pumps are used to reproduce the effect of the EMS on the metal flow. Figure 3 shows schematic sketch of the experimental facility.

As a first step, the water model experiments are based mainly on visualization using an advanced video camera. The water model case list is shown in Table 2. The water model cases are designed to be analogous with the corresponding simulated cases in Table 1. The visualization investigation presented here focuses mainly on the flow pattern and the gas plume structure.

### Table 1

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### Table 2

<table>
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<th>Water pump direction [\text{-}]</th>
<th>Air flowrate [N l/min]</th>
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<th>Gas plug position, radius [R]</th>
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Results

Gas Plume — The plume shape of gas stirring can be greatly influenced by EMS. In Figures 4–7, the four cases with injected gas are plotted. When the EMS is on, one sees a similar flow pattern between the simulated real case to the left and the photos of the lab water model situated to the right side of the picture. The three cases show an excellent agreement in terms of plume shape and bubble distribution in the ladle.

Flow Field — The flow velocity field and the contours of the gas volume fraction are plotted in Figure 8. It is found that the average melt speed is governed mainly by the EMS. In Figure 9, the cases including EMS reach the fully developed flow, at about 25 seconds after start of stirring, with a mean value of 0.5 m/second for upward stirring and 0.7 m/second for downward stirring. In the case where only the argon gas is used, the calculated final average speed is significantly smaller, around 0.05 m/second. This is a clear illustration that the mixing induced by the EMS is much more intense. When using the EMS, the presence of the argon gas and the position of its injection seem to have small influence on the mean speed growth in the melt and its final value in the process. Similar conclusions are drawn in Figure 10, where the turbulent kinetic energy created by the downward stirring is significantly higher than the other cases.

Stirring Energy — Stirring energy is equivalent to the energy input rate into the liquid vessel. Specific stirring energy (stirring energy per mass) has been widely employed to evaluate the mixing process in the melt. For the gas stirring system, the stirring energy is an energy balance with potential energy of the rising bubbles and the thermal expansion work done by the bubbles. Several empirical formulas for gas stirring have been proposed based on this principle.3 For the electromagnetic stirring system, the stirring energy can be calculated by the mechanical power input rate:

\[
\dot{\varepsilon} = \frac{\int \vec{F} \cdot \vec{V} d\Omega}{M}
\]

(Eq. 6)

where

\[
\vec{F} = \text{the stirring force per unit volume},
\]

\[
\vec{V} = \text{the velocity of liquid steel},
\]

\[
M = \text{the weight of liquid steel and}
\]

\[
\Omega = \text{the unit volume}.
\]

In theory, the specific stirring energy input rate shall be equal to the dissipation rate of mechanical energy per unit mass of the system. The dissipation rate of mechanical energy can be calculated as:

\[
\Phi = 2\nu S_{ij} S_{ij} + 2\nu S_{ij} S_{ij}
\]

(Eq. 7)

where

\[
S_{ij} = \frac{1}{2} \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right)
\]

(Eq. 8)
\[ s_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \]  
(Eq. 9)

\( s_{ij} \) = the mean rate of the strain,
\( s'_{ij} \) = the fluctuating rate of the strain,
\( 2\nu s'_{ij}s'_{ij} \) = the viscous dissipation rate of the mean flow,
\( 2\nu s_{ij}s_{ij} \) = the dissipation rate of the turbulent energy,
\( U_i \) = the \( i \)th component of the mean melt velocity and
\( U'_i \) = its fluctuating term that represents the turbulence.

The specific stirring energy can be calculated as:
\[ \dot{\varepsilon} = \frac{\int \Phi d\Omega}{M} \]  
(Eq. 10)

Equation 10 has been used in this work to calculate the stirring energy in a gas stirring system, an electromagnetic stirring system, and a combined stirring system.

The advantages of Equation 10 are that the stirring energy is calculated through the integration in the whole liquid volume, and the

Figure 7
Plume shape of case 6 of numerical respective water model.

Figure 8
Melt velocity and slag interface at ladle mid-plane.
effects of all the factors including slag layer, free surface, stirring force, etc., are accounted for through their influence on the flow speed and turbulence.

Figure 11 shows the calculated stirring energy of three cases with time history. It shows clearly the increase of stirring energy by combined stirring during the developed stage. One interesting feature in this figure is that the stirring energy is bigger during the melt acceleration stage, which means that the intermittent running of combined stirring can probably lead to a higher stirring energy in the melt.

Time history of average melt speed.

Time history of average turbulent kinetic energy in the melt.
Mixing Time — In this study, nine pre-defined points distributed in the melt are used to calculate the mixing time. The appropriate mixing time is reached when the difference between the calculated values and the mean concentration is less than 5%. In Figure 12, a typical graph of the scalar concentration at the nine positions as a function of time is plotted.

The values of the mixing time of the six simulated cases are presented in Table 3. EMS has a much shorter mixing time than gas stirring; the combined stirring can lead to even shorter time compared with only EMS. It has...
also been found that the position of tracer additions has a significant influence on the mixing time, which will not be discussed in this paper.

**Slag Eye Area** — In the six simulated cases, the slag eye opening has comparable size as the published and other reported ones from the real process data. From the results plotted in Figures 13 and 14, it can be concluded that the slag eye opening is due mainly to the EMS. The smallest slag eye in the present study is obtained with only gas stirring, given the simulated cases. It shall be noted that the slag eye area is very sensitive to the slag layer thickness, which is not discussed in this paper.

**Melt/Slag Interface Turbulence** — Local turbulent mixing is the governing process to enhance the reactions at the melt/slag interface. Gas stirring without EMS induces a high turbulence at the jet impact zone on the interface. This effect remains local, and the turbulent kinetic energy averaged on the melt/slag interface is small. The EMS induces progressively a high level of distributed turbulence, which stabilizes at a certain level when the developed flow is reached, as shown in Figure 15.

**Bubbles Volume Fraction and Residence Time** — The gas cleaning capacity is dependent on the quantity of the bubbles’ total surface area and their residence time in the melt at each instant. Figures 16 and 17 show the overall bubble volume fraction and the average residence time in the melt, respectively. When the bubbles are introduced, the melt has a very low average speed and operates like a gas storage tank, where a local maximum mean gas fraction is reached at approximately 4 seconds. Then the melt bulk is sufficiently accelerated to carry the bubbles, until the melt/slag interface is as fast as in the developed flow. Consequently, the bubble accumulation in the melt drops sharply before

### Table 3

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<tr>
<th>Case</th>
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<th>3</th>
<th>4</th>
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<th>6</th>
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<td>Mixing time [s]</td>
<td>160</td>
<td>&gt;400</td>
<td>180</td>
<td>190</td>
<td>95</td>
<td>80</td>
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</table>

**Figure 13**

Slag eye opening at final simulation time, 40 seconds, for all cases. Black circles indicate the porous plug.
slowly increasing, until the flow becomes fully developed. The final value is dependent on the strength of the EMS-induced liquid re-circulations and their capacity to entrain bubbles back in the melt. From the study, it is clear that the upward EMS, together with gas injected at the far side, provides the maximum bubbles for the longest time in the melt, and this is good for the cleaning.

**Discussions**

The results show the flexibility of EMGAS regarding the flow speed, gas plume, stirring energy, slag layer, etc. For desulfurization in

**Figure 14**

Change of slag eye area with time.

**Figure 15**

Time history of average turbulent kinetic energy at the melt/slag interface.
the ladle, a strong gas flow is favorable for creating the turbulence in the slag/metal interface. EMS creates a circulating flow in the whole melt, so that the mixing time is shortened. The slag eye can be easily opened and closed by changing the current of EMS. For the cleaning stage in the ladle furnace, one can use the EMS to control the shape of the gas plume to make full use of the bubble cleaning effect, and at the same time to use the cleaning effect of EMS. The shorter mixing time for several EMGAS cases is also favorable for an efficient heating and alloying process.

Figure 16

Time history of void fraction in the melt.

Figure 17

Bubbles’ average residence time in the melt.
Conclusions
Basic fluid-dynamic features of combined EMS and gas stirring have been studied in the present work. A transient, multi-phase numerical model has been built. Visual investigation of the gas plume shape and flow pattern in a water model has also been done. The results show that EMGAS has a strong flexibility regarding the flow speed, gas plume, stirring energy, mixing time, slag layer, etc. Given the results of the study, it is evident that there is a significant potential to implement EMGAS in the ladle refining process to shorten the production time and/or make cleaner steel. Future work on this project will be focused on the parameter optimization and industrial experiment.

References

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ABB AB Corporate Research, 1
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