Simulation and Performance Results for Electromagnetic Stirring Technology on Arvedi 450-ton Consteel® Furnace

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INTRODUCTION

The Acciaieria Arvedi Group in Cremona, Italy is one of Europe’s most significant steelmaking realities, operating in the production of hot rolled, galvanized and pre-painted coils, carbon and stainless-steel tubes, and stainless-steel precision rolled strip. The well-known innovative ‘Arvedi ESP’ process technology, based on the casting and in-line continuous rolling of a thin slab to a finished coil, allows excellent quality ultrathin steels to be produced with very low energy consumption. To comply with the higher productivity of the recently improved ESP line, Arvedi put an order for a new 450t Tenova Consteel® electric arc furnace (EAF) in 2018 to replace the existing 350-ton Consteel® EAF which was installed in 2008. The new electric arc furnace has a diameter of 9.1 meters and is continuously fed by a 4.0-meters-wide Consteel® conveyor. The productivity of the record-breaking new EAF is 412 ton/hour with a tapping weight of 300 metric tons, a power-on time of 37 minutes, and a charge mix of including up to fifty percent of scrap surrogates as Pig Iron and Hot Briquetted Iron (HBI). This output has never been achieved before by a single EAF, and it is made possible thanks to the proprietary Consteel technology of Tenova, complemented by Consteerrer, an innovative system including ABB ArcSave electromagnetic stirring (EMS). Only the EAF Consteerrer® configuration is currently able to achieve the flexibility, productivity, product quality and production efficiency that are pillars of success at Acciaieria Arvedi. The basic data of Arvedi 450t furnace is shown in Table 1.

Table 1. Basic Data of Arvedi Consteel Furnace

<table>
<thead>
<tr>
<th>Furnace type</th>
<th>Consteel® from Tenova</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace capacity</td>
<td>450 ton</td>
</tr>
<tr>
<td>Heat size</td>
<td>300 ton</td>
</tr>
<tr>
<td>Scrap charge mix</td>
<td>Scrap + Pig iron + HBI</td>
</tr>
<tr>
<td>Bottom inner shell diameter</td>
<td>9.1 m</td>
</tr>
<tr>
<td>EMS stirrer size</td>
<td>ORB65U+</td>
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Consteel® furnace is a typical flat bath operation process, and the melted scrap is not in contact with arcs but rather with the liquid metal. One issue for this Consteel flat bath melting process is the temperature homogenization of the furnace bath, especially in the scrap charging area which is always colder compared to the arc heating area. The temperature difference is reported up to 150 °C for a typical 100-ton Consteel furnace. To solve this problem of inhomogeneous temperature, a tailor-made Consteel solution has been developed through close collaboration between ABB Metallurgy and Tenova S.p.A. The installation of an electromagnetic stirrer underneath the Consteel furnace bottom will increase the mass and heat transfer in the bath, provide a homogeneous temperature distribution and faster scrap melting. In this paper, the effect of electromagnetic stirring on the Arvedi 450t Consteel® furnace process has been studied by both numerical simulation and hot test results.

DISCUSSION

1. Stirring Principle and Stirrer Installation
The electromagnetic stirrer is placed underneath the furnace bottom, where the whole bottom shell is made of a non-magnetic (austenitic stainless steel) steel plate. The low frequency electrical current carried through the stirrer windings generates a traveling magnetic field which penetrates the furnace bottom and in turn generates forces in the molten steel. Since the magnetic field penetrates the full depth of the melt, the melt flows in the same direction across the entire diameter of the furnace and through the full depth of the bath. After reaching the furnace wall the melt has to flow back along the sides of the furnace. When the travelling field is reversed, the melt flows in the opposite direction. Since the stirrer is extended over the entire diameter of the furnace, an effective stirring force is obtained throughout the whole bath. It should be noted that the magnetic force acts not only in a horizontal but also a vertical direction, which results in a more efficient mixing effect on the entire bath. EMS offers the added benefit of having no physical contact with the steel melt which results in very low maintenance requirements. The stirrer configuration for the Arvedi furnace is to generate a traveling magnetic force in a direction along the furnace bottom central plane extending from the slag door to the tapping hole of the electric arc furnace, as shown in Figure 1.

![Figure 1. Electromagnetic stirrer configuration on Arvedi 450-ton furnace.](image)

2. CFD Simulation and Hot Test Results
The stirring force of EMS in the melt is simulated with Dassault Opera and exported to Ansys Fluent to carry out the CFD simulations. The goal of these simulations is to investigate the distribution of melt temperature, velocity, and heat flux transferred to the scrap in the Arvedi 450-ton EBT tapping Consteel® furnace with varying EMS stirring power and steel weight. The bath temperature gradients during the arc power-on period have also been calculated. The scrap charging area is applied as a porous zone, as described in detail in section 2.4.

The performance test was carried out in November of 2021 once the new furnace was in full operation. Following an agreement between Arvedi and ABB, the reference test was started by turning the EMS OFF for a period of 3 days and some 60 continuous heats were collected. The performance test was continued immediately after the reference test by turning EMS-ON for a period of 14 days and around 300 heats were collected. The performance improvements were obtained by directly comparing the process data between the reference heats and performance heats. In the following sections, performance test results have been discussed as a validation of the CFD simulation results.

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2.1 Bath Temperature Homogenization

Bath temperature homogenization is important for reliable bath temperature measurement, improved scrap melting, a high EBT free opening and so on. The effect of EMS on bath temperature homogenization has been calculated with the following assumptions:

1. For starting conditions, the bottom temperature is assumed to be 1560 °C while the surface temperature is 1620 °C. Temperature homogenization times are compared with and without EMS stirring.
2. For the non-stirred bath, natural stirring is simulated with a case of 5% maximum EMS power as a reference.

Temperature homogenization time for cases with stirring direction from slag door to EBT with 5% EMS (left) and 100% EMS (right) for 450-ton heat size are presented in Figure 2. Homogenization time is calculated at the point when the maximum temperature difference between bottom and surface is less than 5 °C. Figure 2 (left) shows 5% EMS power with a calculated homogenization time of 477 seconds. Figure 2 (right) shows 100% EMS power with a homogenization time of 113 seconds. These results show that bath temperature homogenization time with EMS is significantly shorter at only 24% of the time required for homogenization with 5% EMS. The bulk turbulent flow induced by the EMS brings a thorough mixing of the whole melt, resulting in faster bath temperature homogenization.

Bath temperature homogenization was measured in the Arvedi furnace by comparing two repeated temperature measurements at the same location before tapping with standard practice. The first one (T1) was taken immediately after arc power-off and the second one (T2) was taken within 30 seconds after the first one finished. In total, 30 repeated measurements have been performed. With EMS-ON, the average absolute bath temperature difference \( \text{ABS}(T_1-T_2) \) is 9 °C while it is 24 °C with EMS-OFF. It should be pointed out that if the bath temperature homogenization has been measured in two different locations in the bath, the average absolute bath temperature difference might be higher than 24 °C for the case with EMS-OFF. Good homogeneity is important from a metallurgical viewpoint. It implies reliable temperature measurement and more consistent tapping temperature control. The good bath homogenization after Consteerrer® therefore makes it possible to obtain an exact tapping temperature for various steel grades which is very important for smooth downstream ladle furnace operation. Homogenous temperature distribution in the melt bath will give a hot EBT and smooth tapping without delays.

2.2 Melt Velocity Distribution and Scrap Melting

The melt velocity distribution in the Arvedi furnace, simulated by CFD simulation for an intermediate stage with 350-ton liquid steel and solid scrap charging phase is presented in Figure 3. The EMS stirring direction is from slag door towards EBT tapping hole. Figure 3 (top left) shows the velocity distribution on the surface at 50mm offset from melt bottom, and the main flow in the bath center is from the slag door to the EBT and the reflection is on the sides of the bath. Figure 3 (top right) shows the velocity distribution on the surface at 50mm offset from melt top surface. The main reflection flow is from EBT to slag door to the EBT. Figure 3 (bottom left) shows the velocity distribution in the longitudinal cross-section. Figure 3 (bottom right) is the velocity distribution in the transverse cross section. It can be seen from Figure 3 that the whole melt bath is involved in the movement except the scrap charging zone. The optimized average volume velocity of the melt is in the range of 0.2-0.3 m/s. This stirring effect accelerates the homogenization of both temperature and chemical composition, as discussed in section 2.1.

The forced convection induced by electromagnetic stirring as shown in Figure 3 will enhance the melting of larger scrap pieces, pig iron and also HBI. One indication is that the EBT area after tapping is cleaner (less pig iron blockage in the EBT area) with EMS-ON compared with EMS-OFF. The possibility to either increase the scrap feeding rate by 3-4% without changing the specific energy input or reducing the specific energy input but keeping the same scrap feeding rate was also tested.
2.3 Bath Temperature Distribution During Power-On and Tapping Temperature Reduction

In the current simulation, the electrode arc heating effect was included in the CFD models. In the arc heating model, the total active arc power was assumed to distribute into the furnace by 3 parts. These are 55% transferred to the melt by convection; 20% by radiation which is assumed to homogeneously distribute into the melt surface; and 25% as power loss to the furnace wall, roof, and electrodes. The total active arc power input for the Arvedi 450-ton furnace is assumed to be 200MW. The 55% of convection power applied to the bath surface has been assumed as a function of the distance to the center of the electrodes:

$$\text{Arc power input by convection} = P_{\text{convection}} = \int_{0}^{R} \frac{k}{(r+1)^2} \, dr$$

where \(k/(r+1)^2\) is the power distribution at position \(r\); \(k\) is a constant; \(R\) is the bath surface radius; \(r\) is the distance from the calculation point to the center of electrodes.

The initial temperature of the melt is set as 1560°C. Figure 4 presents the temperature distributions for the top surface and the longitudinal cross-section 10 minutes after arc power-on, with steel weight of 350-ton and EMS stirring direction from slag door to EBT. The temperature patterns on the left side in Figure 4 shows 5% EMS power (the case simulated for without stirring) and the right side shows 100% EMS power. It can be seen from Figure 4 (left) that the bath surface temperature and temperature gradient from surface to bottom with 5% EMS power case are higher than with 100% EMS power. The high temperature zone on the surface with 100% EMS power is located mainly in the center of the bath. The average temperature gradient between the surface layer (50mm offset from the surface) and the bottom layer (50mm offset from bottom) has been calculated with varying EMS power. The results are for the cases with stirring direction from EBT to slag door during power-on time and the results are presented in Figure 5. It can be seen from Figure 5 that the average temperature gradient decreases with an increase of EMS power. This reduction in average temperature gradient with EMS will reduce heat loss from the bath surface and increase arc heating efficiency. This is one of the reasons why it is possible to reduce electrical energy using EMS.

It is clear that the reduction in thermal stratification in the melt bath with Consteerrer® also reduces the tapping temperature. It was found that the tapping temperature with EMS-ON was reduced by an average of 18°C without changing the LF first measured temperature. The temperature drop from EAF to LF after tapping is 48°C with EMS-ON and 65°C with EMS-OFF. The temperature drop with EMS-ON in the EAF is 17°C lower than that with EMS-OFF. The tapping temperature reduction will reduce the final oxygen content in the steel and even reduce refractory wearing in the slag-line area.
2.4 Heat Transfer to the Scrap Charging Area and Energy Savings

The purpose of this simulation is to find out the effect of EMS on the heat flow from the melt into the scrap charging volume for flat bath operation. The scrap charging area is applied as a porous zone with 30% penetrability. The scrap charging area in the Arvedi Consteel® furnace is illustrated in Figure 6. The heat flux transferred from the melt to the scrap/melt boundary layer of 50 mm is calculated for cases with varying EMS power as presented in Figure 6 during arc power-on period. The solid scrap temperature is assumed to be constant at solidus temperature of $T_s = 1470^\circ C$, and the initial liquid melt temperature is $T_m = 1560^\circ C$. Temperature distribution depends greatly on the heat source applied to the top layer of the melt. Total power input is the same as described in section 2.3. The equation governing temperature is

$$ \rho C_p \left( \frac{\partial T}{\partial t} + \bar{U} \cdot \nabla T \right) = \nabla \cdot (k \nabla T) $$
where $C_p$ is the specific heat, $J/K/kg$; $\rho$ is the density of steel; $T$ is the bath temperature; $t$ is the time; $k$ is the thermal conductivity, $W/m/K$; $U$ is the melt velocity.

The heat flux $Q_{ms}$ across the surface of the solid scarp charging zone is directly extracted from the simulation results, including both convective heat flow and conductive heat flow across the surface. The effect of EMS stirring power on the energy transferred to the scrap volume during power-on time has been calculated for cases with stirring direction from slag door to EBT and the results are presented in Figure 7. It can be seen from Figure 7 that the integrated heat transferred to the scrap surface layer increases in line with an increase in EMS stirring power. The heat transferred to the scrap layer with 100% EMS is more than 8 times higher than that with 5% EMS. The simulation results show that EMS will increase the scrap melting rate and reduce the temperature gradient in the bath (between the arc heating area and the scrap charging area).

![Figure 6. Illustration of the scrap charging area and the scrap boundary layer in the Arvedi Consteel® furnace.](image_url)

![Figure 7. Effect of EMS power on the heat transferred from the liquid steel to the scrap volume.](image_url)

The arc heat transfer calculation shows that EMS reduces melt surface superheat during arc heating and the heat from the arc is quickly transmitted to the scrap zone through liquid melt. The decrease of surface superheat temperature will reduce heat losses to the furnace wall and roof during power-on period, and thereby reduce the electricity consumption. Simultaneously, the faster heat transfer to the scrap zone will increase the arc heating efficiency and scrap melting rate, and therefore save on furnace process time, which also reduces heat loss. Arvedi hot test results show that the average electrical energy reduction is 3.6% and the power-on time reduction is 3.5% after EMS-ON. The lower electrical energy consumption and lower bath surface superheat also result in a 3.3% reduction in electrode consumption.

### 2.5 Reduction in Final Tapping Oxygen in the Steel

It is known that bath stirring in EAF will push the carbon-oxygen reaction closer to its equilibrium state. This has been proven once again by the test results from Arvedi. The EAF tapping oxygen was reduced by an average of 165ppm with a slight tap carbon increase after EMS-ON. The lower oxygen content in the steel is also thanks to the 18°C lower tapping temperature. These results indicate that with the aid of electromagnetic stirring it is possible to reach a low tapping oxygen while almost maintaining tapping carbon content. It is also seen that the FeO content in the slag is reduced by 2.8% after EMS-ON. Average oxygen content in LF with EMS-ON is 18ppm lower than that with EMS-OFF. The oxygen reduction in the steel, FeO reduction in the carry-over slag, and overall reduction in carry-over slag has resulted in a 5-7% decrease in Al consumption in ladle furnace.

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2.6 Furnace Bottom Refractory

After the EMS came into operation, the bottom refractory was carefully monitored by the Arvedi team. After each shell change the bottom refractory thickness was measured and the remaining average thickness was compared with the data collected between EMS-OFF and EMS-ON. It can be concluded that Consteerrer® has not created any negative effects on the bottom refractory lining as long as the EMS stirring is properly controlled. On the other hand, the use of EMS has a positive effect on refractory wearing before EMS installation there is sometimes bottom refractory wearing from the electrode arcs: the electrodes projected area has higher refractory wearing compared to others area far away from electrodes. This might be due to the small hot heel and high arc power input in the furnace. After having EMS in operation with increased hot heel, this problem has never happened.

CONCLUSION

The effect of Consteerrer® (EMS) on bath temperature homogenization, stirring power, temperature gradient during arc power-on, and heat transfer from arcs through liquid metal to scrap in the 450-ton Consteel® furnace at Arvedi has been investigated via numerical modelling and industrial tests. Simulation results show that the temperature gradient between furnace bottom and surface during arc power-on is reduced from 176°C without EMS to 37°C with 100% EMS power, and the heat flux transferred to the scrap boundary layer with 100% EMS power is 2-3 times higher than without EMS. Site acceptance test results show that EMS increases are heating efficiency and scrap melting rate, reduces electric energy consumption, power-on time, and oxygen content in the steel, as well as increasing scrap yield. The guaranteed KPIs with EMS are fully achieved as part of the Arvedi project. The process benefits obtained from EMS are presented in Table 2.

Table 2. Process Improvements After Consteerrer® Installation at Arvedi

<table>
<thead>
<tr>
<th>No.</th>
<th>Process parameters</th>
<th>Performance improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Temperature homogenization (°C)</td>
<td>&lt; 9 °C</td>
</tr>
<tr>
<td>2</td>
<td>Tapping temperature reduction (°C)</td>
<td>-18 °C</td>
</tr>
<tr>
<td>3</td>
<td>Temperature drop from EAF to LF (°C)</td>
<td>-17 °C</td>
</tr>
<tr>
<td>5</td>
<td>Electric energy reduction (kWh/tls)</td>
<td>-3,6%</td>
</tr>
<tr>
<td>6</td>
<td>Power-on reduction (min/tls)</td>
<td>-3,5%</td>
</tr>
<tr>
<td>7</td>
<td>Electrode reduction (kg/tls)</td>
<td>-3,3%</td>
</tr>
<tr>
<td>8</td>
<td>Productivity increase (ton/h)</td>
<td>+4,5%</td>
</tr>
<tr>
<td>9</td>
<td>Final oxygen reduction in EAF steel (ppm)</td>
<td>-165ppm</td>
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<tr>
<td>11</td>
<td>First oxygen in LF (ppm)</td>
<td>-18 ppm</td>
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<tr>
<td>12</td>
<td>FeO content in EAF slag (%)</td>
<td>-2,8%</td>
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<tr>
<td>13</td>
<td>Scrap yield (%)</td>
<td>+0,6%</td>
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<tr>
<td>14</td>
<td>Refractory wear</td>
<td>Better</td>
</tr>
<tr>
<td>15</td>
<td>Carry-over slag</td>
<td>Less</td>
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</table>

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