An experimental activity has been performed to monitor the trend in slag–metal composition and temperature during the process of oxidation within an EAF system equipped by multi-burner injection system in which the injectors are distributed along the circumference of the furnace side-walls. This issue is a fundamental aspect to achieve a good balance for reaching the metallurgical goals and the energy savings necessary to maintain a good mix between the chemical specifications and the energy efficiency. The last aspect represents one of the most important bases to grant the competitiveness of the plant. A reliable interpretation of the data obtained from the industrial plant can also be evaluated through the use of the predictions performed by a developed simulation model.  

KEY WORDS: oxygen injection; carbon injection; steel oxidation; electric arc furnace; steel refining; energy; Enthalpy.
ter: a jet with an impinging point too near to the refractory walls can cause an excessive consumption of the refractory, while a jet too less inclined with the respect to the horizontal can produce splashing of the hot steel. A good compromise is an injection angle between 41° and 44° degrees from the vertical direction.

This work is aimed at increasing the understanding of the performances and effects of the oxygen supersonic jets produced by a multi-point side-wall system on the decarburization rate of the bath, on the oxidation of the other alloying elements and on the stability of the foamy slag during the refining period. The melting experiments have been realized and monitored within a real scale EAF furnace with a nominal capacity of 105 tons. The experiments have been performed at the Tenaris–Dalmine plant at Dalmine (Italy) and they have been focused on the phenomena that take place during the so-called refining period. The main objective is to establish the relationship between the decarburization rate, the change of the slag composition and the technological parameters ruling the oxygen injection. The experimental results were compared with the results of a formerly validated mathematical model, in order to predict any change of the process evolution as function of the technological parameters chosen for the working of the multi-injection system.

2. Experimental Procedure

The Tenaris–Dalmine EAF is a 105 tons. furnace alimented by three-phases current supplied by a 100MVA transformer.

The furnace has a diameter of about 6 m and it is equipped with three burners, three fixed supersonic lances (Techint KT lances), two carbon injectors and a movable door lance able to act as a burner, as a supersonic lance and as a carbon injector.

The KT lances installed in the plant can blow from 200 to 2000 Nm$^3$/h of oxygen into the steel. They are placed inside the furnace walls at an angle of 40° from the horizontal and at an height of 400 mm above the steel line (during the refining period).

The movable door lance maintains a fixed position during the refining period, and it operates at a height of about 150 mm above the steel line with an injection of oxygen at 42° from the horizontal with flow rate which can vary from 40 to 4000 Nm$^3$/h. During the refining period the three KT lances do not work as burners, so this peculiar effect is not taken into account in this work. Due to the height of installation the lances operate directly inside the slag during the refining period.

During the refining period the door lance operates with a 3500 Nm$^3$/h oxygen flow rate, two KT lances with 1250 Nm$^3$/h oxygen flow rate and one KT with 1400 Nm$^3$/h oxygen flow rate. The burners are turned off (pilot flame). The average of the total carbon consumption is 3.8 kg/ton for every heat.

The experiments consisted in the sampling of a series of iron and slag taken at the beginning of the refining period and in four successive moments at a constant time step over a set of 153 heats which could be regarded as homogeneous from the point of view of the type of the chemical composition and geometrical features of the scrap.

The samples were taken automatically from the bath by an electro-mechanical robot and, when it was not possible (for example when the bath was too cold), manually by the operator through the door lance. The temperature and the oxygen activity measurements were performed through the use of the Celox® method.

The measurements aim is to diagram the trend of the composition of the steel bath and of the slag during the refining period. The concentration of silicon and aluminium is very low in this phase of the furnace elaboration. For this reason the experimental instruments used for the quantitative determination of the chemical analysis (spectrometers) do not turn out significant values.

The evaluation of the performances has been evaluated through a comparison among the heats melted by a traditional system featured by a specific oxygen rate of 30 Nm$^3$/ton of steel and the heats melted through a multi-point side-wall system featured by an average specific oxygen rate of 38 Nm$^3$/ton of steel.

3. Results

The first step of this analysis was the monitoring of the bath composition from the beginning of the refining period (defined as the moment at which the solid charge is completely melted) until the tapping (Figs. 2–5). Every point of the diagram represents a set of trials performed at a fixed time and the minimum and the maximum recorded values have been indicated by the error bar. They have their centre at the average value for concentration for that set of trial and a radius equal to the standard deviation. These results are calculated after the application of the Chauvenet criteria to determine the significant values that should be taken into account: the use of this algorithm allows to perform an au
omatic choice between the representative and consistent values and the not consistent ones, so that this analysis has been developed by discarding the non significant values and concentrating the attention only on the reliable data.

The last measurement sampling has been performed after the furnace tapping: this has been assimilated to the composition of liquid steel and slag left in the furnace. These values can lead to important considerations about the equilibria between liquid steel and slag, since no oxygen and no electrical power is injected into the furnace during the tapping time.

The experiments were all completed on an industrial furnace and only the most similar heats (in a three months period) have been considered for this analysis, nevertheless in spite of all the efforts made to keep the different heats as much similar as possible, there is a little deviation, about 16.5%, in the trial times.

The same procedure was applied to the oxides in the slag.

As seen in Fig. 6 the FeO concentration increases during all the refining period and in particular the oxidation velocity augments in the last part of the period before tapping. This can be easily explained by the consumption of the other chemical species oxidized.

The whole electrical average consumption for the refining period is 120 kWh/t, while the average value for oxygen is 902 Nm$^3$/h and 89.7 Nm$^3$/h for shrouding methane.$^5$

Foamy Slag

During the refining period in Tenaris–Dalmine Furnace the basicity index, Ib3 index, has an average value of 1.5 with a little standard deviation of ±0.04, while Ib2 index, defined as:

$$\text{Ib2} = \frac{\text{CaO}}{\text{SiO}_2}$$  \hspace{1cm} (1)

is 2.1. The average temperature of the slag is 1356°C.

Provided these parameters it is possible to show the slag composition in an isothermal saturation diagram$^6$ (ISD).

The ISD diagrams are maps built upon the CaO–MgO–SiO$_2$–FeO system at a fixed temperature and ternary basicity (Ib3):

$$\text{Ib3} = \frac{\text{CaO}}{\text{SiO}_2 + \text{Al}_2\text{O}_3}$$  \hspace{1cm} (2)

For the conditions described above, the ISD diagram is illustrated in Fig. 7.

During the refining period the FeO–MgO concentrations vary as shown in and those points are represented in the ISD diagram.$^6$

The path followed during the refining period is inside the field featured by the liquid phase saturated with magnesio-
wustite (MgO·FeO$_x$−MW). This assures the presence of a solid phase dispersed inside the liquid slag and the MgO saturation needed to avoid excessive refractories consumption. The presence of MW improves the stability of the foamy slag and the saturation by MgO prevents the wear of the MgO lining by the chemical etching.

4. Discussion

Once obtained the data showed in the former section, the second step of this analysis is their implementation and interpretation by the application of a simulation model based on the description of oxidation phenomena.\(^7\)

A focus on energy balance, between the oxidation of the steel bath and the reduction of the slag, has been performed. The aim is not only the quantitative description of the evolution of the bath composition, but also the evaluation of the total developed chemical power taking into account the main effects of the oxygen and carbon injection.

The energy developed by a chemical reaction, at constant pressure, is the enthalpy of the reaction and it can be easily calculated through the Hess formula.

\[
\Delta E_j (J) = \Delta H_j \left( \frac{J}{mol} \right) [x(t) - x(t + \Delta t)] \text{(mol)} \quad \ldots \ldots \ldots (3)
\]

where \(\Delta H_j\) is the enthalpy associated to the \(j\)-th reaction and can be easily evaluated, once known the values for the enthalpy at standard conditions for every reaction considered.

In the refining period two kinds of reactions are considered: the oxidation of the elements in the bath and the reduction of oxides in the slag:

\[
x[M_e] + O_2 \rightarrow y(Me_{x/y}O_{y/2}) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4)
\]

\[
\frac{1}{y} (Me_{x/y}O_{y/2}) + C \rightarrow \frac{x}{y} [Me] + CO \uparrow \quad \ldots \ldots \ldots (5)
\]

The production of CO$_2$ is neglected at the temperature of the bath during the refining period since the corresponding Gibbs function has a much higher value than the CO one.

The next step is the description of the oxidative process and the determination of the number of moles reacting at a certain time.

For both these aims the thermodynamic potentials give help. Actually, the calculation of oxygen (for oxidation reactions) and carbon (for reduction reactions) potentials shows that the most important elements (either for concentration in the bath/slag, and for their attitude to react) to be considered are iron, carbon, aluminum, silicon, chromium, manganese and their relative oxides.

Phosphorus should be considered as well, but the chemical aspects that determine its presence in the bath are more complex than those utilized here, for this reason the concentration evolution has not been considered, although it has been measured (Fig. 4).

Studying the evolution of the calculation through the structured numerical model\(^1\) it is possible to clarify some aspects of the experimental data previously presented.

The decarburization curve shows the oxidation of the carbon performed by the injected oxygen (Fig. 10). The transport phenomena related to carbon are dominated by its diffusion in the molten metal towards the surface reaction and this result is supported by the literature about this topic.\(^7,8\)

For experimental chromium trend, the experimental results show that its concentration remains substantially unchanged during the process. This fact is explained by the
model through the equilibrium $[\text{Cr}] \leftrightarrow (\text{Cr}_2\text{O}_3)$: the oxygen injected in the bath oxidates [Cr], but (Cr$_2$O$_3$) is simultaneously reduced in the slag by the introduction of C. In this way the global concentration tends to be constant.

The case of Mn is different: in the condition simulated (1600°C, 0.096% [Mn]) the oxygen potential is higher than the iron one. This means that the iron itself protects it from the oxidation, and following this approach Mn concentration does not vary much (except for the concentration effect due to the dilution of other species in the molten metal).

For silicon and aluminium the model predicts a continuous oxidation but the experimental instruments used for their revelation, have not given significant and reliable results as noticed before.

The FeO$_x$ in slag shows a constant increasing in concentration to the value of about 39.4% that is required to reach an adequate oxygen activity in the steel bath which can assure a deep decarburization to an average value of 0.056% C.

Since the model can calculate the number of reacting moles in a certain time step, the Eq. (3) can be used to estimate the global energy developed by the injection plant during the refining period. It consists in the sum of oxidation contributions and the subtraction of the reduction ones, because these last kinds of reactions are endothermic.

$$E = \sum_j x_j \cdot \Delta H_{j,\text{exothermic}} - \sum_j x'_j \cdot \Delta H_{j,\text{endothermic}} \quad \cdots \quad (6)$$

The average results of the simulation performed on the Dalmine furnace have been determined (Fig. 11).

The results show that the most significative contribute is due to the oxidation of Fe, but also C, Mn and Cr contributes are remarkable.

This fact can be explained by the convergence of two main factors: the specific energy oxidation (and reduction) of the elements and the number of moles reacting.

The oxidation of Al in the bath (Fig. 12) has the higher specific enthalpy, but there is a very small amount of Al in the Tenaris furnace, so the overall enthalpy developed by other elements is higher.

A comparison between Figs. 10 and 11 shows that the high oxidation of the Fe in the bath is the main source of energy during the refining period, since the amount of carbon and other thermogenic elements is very low.

The trend of the number of moles oxidized in the bath and reduced in the slag evaluated by the model shows a constant oxidation and reduction of all the species taken into account.

According to the model and to the experimental observations the KT injection plant in Tenaris–Dalmine gives 1790 kWh during refining period (that is period in which the oxygen lances work in the supersonic regime). This result considers both the effects of reduction of the slag and oxidation of the metal.

The overall average electrical consumption is about 5000 kWh measured in the same period. This means that the chemical energy (for both carbon and oxygen injection) contributes for 26.45% of the total power supplied, while 73.55% comes from the electrical arc.

The chemical contribution is higher if we do not consider the effects of the reduction effect of the carbon injection. From these results it has been possible to estimate the liquid bath yield during the refining period for each element taken into account. For example in the most significative case of iron:

$$\eta_\text{Fe} = \frac{[\text{Fe}]_{\text{end}}}{[\text{Fe}]_{\text{beginning}}} \quad \cdots \quad (7)$$

This leads to a Fe yield of 99%. For the other elements results are reported in Table 2.

On the other hand, it is worth noting the comparison between the performances of the new configuration of the injection system based on a multi-point configuration has permitted to reduce the electrical consumption per ton of the melt steel from 390 to 380 kW/ton and the electrode consumption from 1.5 to 1.4 kg/ton. The period in which the power of the electric arc is switched on has resulted in 2 min less and the one in which the electric is switched off is decreased of 1% than that before, thanks to the better ef-

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Table 2. Yield of the other monitored elements in the bath during the refining period.

<table>
<thead>
<tr>
<th></th>
<th>Cr</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>Ni</th>
<th>Mo</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>YIELD</td>
<td>96.84%</td>
<td>92.78%</td>
<td>37.50%</td>
<td>166.67%</td>
<td>77.46%</td>
<td>65.63%</td>
<td>60.00%</td>
</tr>
</tbody>
</table>
ficiency of the oxygen impinging the steel which is lost in the atmosphere in less amount than in the traditional oxygen injecting system. The better homogeneity of the oxidizing action developed within the melt bath has permitted to stabilize the foamy slag (with a beneficial effect also in a decreasing of the refractory wear) because the concentration of the produced FeO is distributed more uniformly than in the case of a traditional injection system. The average weight percentage concentration FeO content of the foamy slag in the traditional system (in the region of the impinging jet) is always higher than 40.9% while the one of MgO is always less than 6.6%. Thus, the slag is led into the liquid phase region featured by the absence of foaming.

5. Conclusions
In order to save electrical power in the furnace operations a multiple injection device featured by super-sonic velocity has been tested. This work is focused on the refining period of the EAF melting process, during which the oxygen lances work in the supersonic regime. An industrial real scale plant has been observed by quantitative measurement of the composition of the steel bath and the slag and the results have been interpreted by the use of a formerly validated simulation model of the oxidation phenomena. The performed experimental procedure and a validated simulation model, used for the interpretation, have permitted to measure the evolution of the chemical composition of the slag and of the steel bath. The comparison among the results obtained through the multi-injection system (in this case a KT© system has been studied) and those obtained by a traditional one has shown the better efficiency of the first one. Actually, it allows to maintain the stability of the foamy slag and to grant a saving of the electrical energy. The electrical energy savings with respect to a traditional oxygen injection system is of about 2.6%, but it is worth noting that the average electrical energy savings which can be permitted by the multi-point supersonic oxygen injection is of 27% of the total electrical energy which has to be used for a melting process performed without the development of heat obtained from the chemical oxidation reactions. Although the significant recorded energy savings, confirmed by the experimental observation and by the model prediction, the average iron loss is only of 1.2% of the charged quantity and the chromium content of the steel bath do not show any significant decrease.

Nomenclature

- $t$: Time (s)
- $E$: Energy (J)
- $\Delta H$: Enthalpy variation (J/mol)
- $x$: Number of mole (mol)
- $[\cdot]$: Concentration of a specie in the steel bath (mol/m³)
- $(\cdot)$: Concentration of a specie in the slag (mol/m³)

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