1. Introduction

Vacuum processes are important in the production of high quality steels, particularlyInterstitial Free and Ultra Low Carbon Steels, with carbon concentrations of less than 20 ppm. These steels have large application in the automotive industry.

The RH degasser is a secondary refining process that can simultaneously attain significant levels of removal of these interstitial elements from liquid steel. In the RH process, the melt circulation rate plays a very important role in determining productivity of the equipment, since it affects the decarburization rate.

In the present work, a physical model of a RH degasser in a 1:5 scale of an industrial reactor from USIMINAS (Minas Gerais, Brazil). This model has been built and used in the study of the circulation rate and of the kinetics of decarburization. The effects of the gas flow rate and of the configurations of the nozzles used in the injection of the gas have been analyzed. The effect of gas injection in the vacuum chamber was also investigated.

The decarburization reaction of liquid steel was simulated using a reaction involving CO$_2$ and caustic solutions. The concentration of CO$_2$ in the solution was evaluated using pH measurements.

The experimental results indicated that the kinetic of decarburization is controlled by mass transfer in the liquid phase. It was also observed that, in certain configurations, the injection of gas in the vacuum chamber can increase the decarburization rate.

KEY WORDS: RH degasser, decarburization rate, melt circulation and secondary refining.
two parts, one to evaluate the melt circulation and the other to study the decarburization rate. These experiments are described below, after a description of the physical model and of the experimental apparatus.

2.1. Experimental Apparatus

Figure 1 shows a schematic view of the physical model of the RH degasser with the sensors used in the tests. Table 1 presents the dimensions of the physical model and the main characteristics of the gas injection system. To analyse the effects of gas injection directly into the vacuum chamber, 12 nozzles were used. They were placed at the bottom of the vacuum chamber, symmetrically distributed along the perimeter of the upleg snorkel. These nozzles are shown in Fig. 2.

The Fig. 2 also details the positions of the pH sensors used in the test to analyse the better position and its effects in the kinetics of decarburization. This test was done with gas injection only in the upleg snorkel and using a standard gas flow rate of 200 STP L/min for all the positions (1, 2 and 3). The Table 2 shows that the rate constant of the reaction (K) is not influenced by changing the position of the pH sensor. The position 1 was chosen to make possible a better base support to the pH sensor. The conductivity position sensor was used for many authors and comes from the concept of the circulation rate. The circulation rate of liquid in a RH degasser can be understood as the amount of steel passing through a plane perpendicular of the downleg snorkel per unit of time.

2.2. Experiments

During the experiments, air supplied by a compressor was injected into the upleg snorkel and into the vacuum chamber. The flow rates in these two regions were measured by mass flowmeters and controlled manually. There were no individual measurements of flow rate for each nozzle. To equally distribute the gas among the nozzles, the air was first injected in the central region of two small chambers. These chambers were connected to each nozzle using pipes with the same length and diameters.

The pressure in the vacuum chamber was controlled manually using a system of valves and monitored by a pressure gauge. The levels of water in the ladle and in the vacuum chamber were controlled and kept constant in all the experiments.

Similarity between the physical model and the industrial plant was established using the Froude and the modified Froude dimensionless numbers.

Two types of experiments were conducted in the present work:
- experiments to evaluate the melt circulation;
- experiments to determine the decarburization rate.

During the experiments, images of the plume (top region

![Diagram](image-url) Fig. 1. Schematic view of the physical model of the RH with the sensors used in the tests.

Table 1. Characteristics of the physical model and of the gas injection system.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ladle</td>
<td></td>
</tr>
<tr>
<td>- larger diameter (m)</td>
<td>0.720</td>
</tr>
<tr>
<td>- smaller diameter (m)</td>
<td>0.648</td>
</tr>
<tr>
<td>- height (m)</td>
<td>0.760</td>
</tr>
<tr>
<td>- the level of the liquid (m)</td>
<td>0.680</td>
</tr>
<tr>
<td>Vacuum Chamber</td>
<td></td>
</tr>
<tr>
<td>- diameter (m)</td>
<td>0.420</td>
</tr>
<tr>
<td>- height (m)</td>
<td>0.712</td>
</tr>
<tr>
<td>- the level of the liquid (m)</td>
<td>0.695</td>
</tr>
<tr>
<td>- relative pressure (Pa)</td>
<td>-2850</td>
</tr>
<tr>
<td>Snorkel</td>
<td></td>
</tr>
<tr>
<td>- length (m)</td>
<td>0.312</td>
</tr>
<tr>
<td>- diameter (m)</td>
<td>0.127</td>
</tr>
<tr>
<td>- immersion depth (m)</td>
<td>0.135</td>
</tr>
<tr>
<td>- distance between the centres (m)</td>
<td>0.269</td>
</tr>
<tr>
<td>Gas injection</td>
<td></td>
</tr>
<tr>
<td>- gas flow rate total (STP L/min)</td>
<td>500</td>
</tr>
<tr>
<td>- nozzles inside the upleg:</td>
<td></td>
</tr>
<tr>
<td>- gas flow rate (L/min)</td>
<td>50 - 450</td>
</tr>
<tr>
<td>- number</td>
<td>10</td>
</tr>
<tr>
<td>- diameter (mm)</td>
<td>1.0; 1.5; 2; 2.5</td>
</tr>
<tr>
<td>- position below the liquid level in the ladle(m)</td>
<td>0.075</td>
</tr>
<tr>
<td>- nozzles inside the vacuum chamber:</td>
<td></td>
</tr>
<tr>
<td>- gas flow rate (STP L/min)</td>
<td>50 - 450</td>
</tr>
<tr>
<td>- number</td>
<td>12</td>
</tr>
<tr>
<td>- diameter (mm)</td>
<td>1.0; 1.5; 2; 2.5</td>
</tr>
</tbody>
</table>
of the upleg snorkel and vacuum chamber) were captured. These images were post processed to estimate the plume area for each experimental condition.

2.2.1. Melt Circulation Rate

To determine the melt circulation rate, the method used by Seshadri and Costa\textsuperscript{2} was adopted. In this procedure, a solution of potassium chloride is injected in the upleg snorkel in the form of a pulse. The concentration of KCl in the downleg is then continuously monitored. Since the electrical conductivity of water is affected by the presence of KCl, its concentration is calculated based on the signal generated by the electrical conductivity sensor, using a calibration curve previously determined.

The circulation rate was estimated using the following equation:

\[ \Gamma = \frac{V}{A/\Delta C} \]  

The \textbf{Fig. 3} illustrates an experimental curve representing the variation of concentration of KCl in the downleg snorkel as a function of time. The circulation rate founded for the conditions presented in the Fig. 3 is 6.32 ± 0.04 kg/s.

To guarantee the reliability of the experiments, the mass balance of KCl was verified in all the tests. Ten experiments were carried out for each experimental condition. This method was also used by Almeida \textit{et al.},\textsuperscript{1} Silva \textit{et al.},\textsuperscript{3} and Vargas.\textsuperscript{4}

2.2.2. Decarburization Rate

The desorption of CO\textsubscript{2} from caustic solutions was used to simulate the decarburization reaction of liquid steel.\textsuperscript{2} In these experiments, CO\textsubscript{2} was injected into an aqueous solution of sodium hydroxide (NaOH) with a concentration of 0.01 g · mol/L, until the pH reached a preset value (approximately 6.5). At this point, the operation of the RH physical model was started, with the injection of air in the upleg snorkel. This injection leads to CO\textsubscript{2} desorption and to an increase in the pH of the circulating fluid. The variation of the pH was monitored during the entire test at a frequency

<table>
<thead>
<tr>
<th>Gas Flow rate (STP l/min)</th>
<th>K (s\textsuperscript{−1})</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.0039</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>0.0034</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>0.0038</td>
<td>3</td>
</tr>
</tbody>
</table>

\textbf{Table 2.} Experimental K values with the pH sensors positions.

\section*{Fig. 2.} Details of the sensors and nozzles used in the tests.

\section*{Fig. 3.} Experimental curve showing the variation of KCl concentration at the downleg snorkel as a function of time.
of 0.33 Hz. A calibration curve was used to convert pH values into aqueous CO₂ concentration. Different locations for the pH sensor were adopted, without significant difference in the results. Air flow rates distributed between the upleg snorkel and the vacuum chamber were used in the tests. The sum of the flow rates were kept constant at 500 STP L/min, due to limitations of the air compressor. Nozzles with diameters of 1.0, 1.5, 2.2 and 2.8 mm were also tested in the simulations. The remaining conditions were kept constant in all experiments. Three experiments were run for each experimental condition.

It was assumed that the desorption rate of CO₂(aq) could be expressed by the following equation:

\[ \frac{dC_{CO₂(aq)}}{dt} = K \cdot (C_{eq}^{CO₂(aq)} - C_{CO₂(aq)}) \ldots \ldots \ldots \ldots \ldots (2) \]

This equation can be integrated to obtain Eq. (3).

\[ -\ln \left( \frac{C_{CO₂(aq)} - C_{eq}^{CO₂(aq)}}{C_{CO₂(aq)}^{i} - C_{eq}^{CO₂(aq)}} \right) = K \cdot t \ldots \ldots \ldots \ldots \ldots (3) \]

2.2.3. Images of the Plume in the Vacuum Chamber

The rates of the decarburization and degassing reactions, which occur mainly in the vacuum chamber, depend on the contact area between the liquid metal and the gas.\(^7\)

To establish a qualitative comparison of the contact area between the liquid metal and the gas in the different conditions adopted in the experimental tests, images of the plume in the vacuum chamber were captured. For each experimental condition, ten images were post processed to estimate the plume area inside the vacuum chamber. A public domain software called ‘Image J’ was used to estimate the area of the plume and the total area of fluids inside the vacuum chamber.

3. Results and Discussion

Initially, the effects of gas injection into the vacuum chamber on the melt circulation and decarburization rates were evaluated. Based on these rates, values of volumetric mass transfer coefficient were deduced. An operational condition that optimizes the decarburization rate was determined.

It is important to mention that, in tests with gas injection into the vacuum chamber, the total gas flow rate (upleg and vacuum chamber) was kept constant at STP 500 L/min.

To analyse the experimental results of melt circulation and decarburization rates, surface plots involving the different variables investigated were built. The results with gas injection into the vacuum chamber were also compared to those obtained by Almeida et al.,\(^1\) with gas injection only in the upleg snorkel.

3.1. Effect of Gas Injection into the Vacuum Chamber on the Melt Circulation Rate

The variation of the melt circulation rate as a function of gas flow rate injected into the vacuum chamber is presented in Fig. 4.

For a given diameter of the nozzles used in the vacuum chamber, the circulation rate tends to increase when the gas flow rate in the vacuum chamber decreases. Since the total gas flow rate was kept constant, an increase in the gas flow rate in the vacuum chamber leads to a reduction in the gas flow rate in the upleg snorkel. This reduction decreases the gas lift in the upleg snorkel and causes a decrease in the circulation rate. Another factor that should be considered is that, in the vacuum chamber, the gas was injected along the entire perimeter of the upleg snorkel. The gas injected in the nozzles placed between the upleg and downleg snorkels might have limited the flow in the central region of the vacuum chamber and caused the reduction in the circulation rate.

There is also a tendency of the melt circulation rate to increase with an increase in the diameter of the nozzles in the upleg snorkel. There is also noted that the circulation rate has remained around ~6 kg/s, considering the weight of the liquid in the ladle (250 kg), the mixing time is 0.7 min (250/6=42 s). Based on the modified Froude number, the mixing time of the physical model has a relation with the square root of the RH degasser from the plant (1.5^2=2.25). So the mixing time of the physical model turns to 1.57 min (0.7 · 2.24). Considering that the results of the mixing time of the plant is about 1.5–3 min, the result of the physical model of the RH degasser is representative.

Other authors\(^1,2,4\) found similar results to this study with gas injection only in the upleg snorkel.

Figure 4 also indicates that the diameter of the nozzles of the vacuum chamber did not present a significant effect on the melt circulation rate.

It is also interesting to observe that for nozzles with 2.2 mm diameter there appears to be a condition that optimizes the circulation rate. This maximum in the circulation rate was attained with flow rates of 150 and 350 STP L/min in the vacuum chamber and upleg snorkel, respectively.

3.2. Effect of Gas Injection into the Vacuum Chamber on the Decarburization Rate

Figure 5 presents a plot of the experimental data based on Eq. (3). This experimental data is made using as an example such conditions: gas flow rate of 250 STP L/min and nozzles diameters of 1 mm in the upleg snorkel; gas flow rate of 250 STP L/min and nozzles diameters of 2.2 mm in the vacuum chamber. The graph indicates that the results are well reproduced by this equation. The value of the rate constant K is given by the slope of the straight line.

The variation of the rate constant K with the gas flow rate in the vacuum chamber, for the different nozzle diameters, is shown in Fig. 6.

Except for the experiments with nozzles with diameter of 1 mm in the vacuum chamber, the results for all the other configurations of nozzles are very similar.

For a given flow rate, despite giving the lower circulation rates, the nozzles with smaller diameters tend to lead to higher reactions rates. In the almost all of the experiments, the best results in terms of reaction kinetics were obtained with nozzles of 1.5 mm diameter in the upleg snorkel and with no gas injection in the vacuum chamber. When nozzles with 1 mm diameter are used in the vacuum chamber and in the upleg snorkel, the highest reaction rate is ob-
tained with gas flow rates of 50 and 450 STP L/min in the vacuum chamber and upleg snorkel, respectively.

These results can be analysed considering the variation of the volumetric mass transfer coefficient and the plume area in the vacuum chamber.

3.3. Volumetric Mass Transfer Coefficient

Values of the volumetric mass transfer coefficient for the decarburization reaction can be estimated using Eq. (4), proposed by Yamaguchi et al.\textsuperscript{11)}

\[ K = \frac{1}{W\left(\frac{1}{T} + \frac{1}{\alpha k \cdot \rho}\right)} \]  \hspace{1cm} (4)

This equation was developed considering the following assumptions

- the reaction rate is controlled by mass transfer in the liquid;
- the liquid is perfectly mixed in the ladle and in the vacuum chamber;
- the amount of liquid in the ladle is much larger than that in the vacuum chamber.

All these assumptions are reasonable in the conditions adopted in the present investigation. The first assumption is valid when the carbon concentration is smaller than 200 ppm.\textsuperscript{11)}

The values of the volumetric mass transfer coefficient \( a \cdot k \) calculated according to Eq. (4), are shown in Fig. 7.

The trends observed in Fig. 7 are very similar to those shown in Fig. 6. The best result in terms of the volumetric mass transfer coefficient was obtained with nozzle diameter of 1 mm and flow rate of 50 STP L/min in the vacuum chamber and 450 STP L/min in the upleg snorkel.

The volumetric mass transfer coefficient was then plotted as a function of the relative plume area in the vacuum chamber, estimated by images analysis. The results are presented in Fig. 8.

Despite the dispersion of the points in the Fig. 8, there is a clean tendency of the volumetric mass transfer coefficient to increase when the relative plume increases.

This is clearly noted in the results presented in Table 3 for the nozzles diameter of 1 mm in both, the upleg snorkel and in the vacuum chamber. Also the best result obtained on the kinetics of the reaction is shown in this table. How can be seen the best rate constant of the reaction (0.0079 \( \text{s}^{-1} \)) is reached when the percentage of plume area into the vacuum chamber is highest. Table 4 presents the results for the nozzle diameter of 2.2 mm in both, the upleg snorkel and in the vacuum chamber. The kinetics of decarburization
here has behaved differently in relation to the circulation rate, because, even with the increased of the circulation rate, the kinetics of decarburization had a decreased, as can be noted for the gas flow rate of 250 STP L/min in the upleg snorkel and the vacuum chamber. This can be explained due to the kinetics of decarburization depends not only from circulation rate of the process, but also from the volumetric mass transfer coefficient. It is due to the volumetric mass transfer coefficient to measure the intensity of occurrence of this reaction, because it involves, besides the circu-

Fig. 6. Variation of the rate constant $K$ with the gas flow rate in the vacuum chamber, for the different combinations of nozzles diameters. V.C.: the diameter of nozzles in the vacuum chamber (mm).

Fig. 7. Volumetric mass transfer coefficient for the different configurations of nozzles and gas flow rates in the vacuum chamber. V.C.: the diameter of nozzles in the vacuum chamber (mm).
The reaction rate, the area where the reaction occurs and the concentration of the element removed from the bath.

Figure 8 also shows that the percentage of the plume area occupies between 20 to 55% within the vacuum chamber, with its highest concentration between 25–35% which have volumetric mass transfer coefficient between 0.0010 and 0.0015 m³/s. This area represents the percentage of the plume area where the diffusion reaction occurs from the interstitial elements of the steel such as: C, N and H. Note that there is a growing trend in the volumetric mass transfer coefficient when the nozzles diameter of the gas injection was decreased. This trend is observed with increasing agitation of the liquid inside the vacuum chamber, increasing the splash and consequent increase in the intensity of the reaction.

These results indicate that higher decarburization rates are attained when the plume area is increased. The effect of the circulation rate on the decarburization kinetics is secondary.

In the present investigation, the best results in terms of decarburization rates were obtained with low melt circulation rates but high plume area. This evidence contradicts the common belief that increasing the circulation rate necessarily leads to faster decarburization.

4. Summary and Conclusions

In the present investigation, a physical model was used to study the circulation rate and the kinetics of decarburization in RH degasser. The effects of the gas injection into the vacuum chamber and of the diameters of the nozzles used in the gas injection were investigated. In all the experiments, the total gas flow rate was kept constant at 500 STP L/min. The decarburization of liquid steel was simulated using reaction of desorption of CO₂ from caustic solutions.

The results showed that the circulation rate increases with an increase in the diameter of the nozzles and decreased when the gas was injected in the vacuum chamber. The kinetics of the reaction follows a first order equation and is controlled by mass transfer in the liquid phase. The reaction rate constant was affected by the gas flow rate and the nozzles diameters. An increase in the gas flow rate in the vacuum chamber tends to reduce the decarburization rate. This trend was observed for all nozzle combinations, except when nozzles with 1 mm of diameter were used. In this case, the best result was attained with gas flow rate of 50 STP L/min in the vacuum chamber and 450 STP L/min in the upleg snorkel.

The positive result obtained for gas injection into the vacuum chamber was injected in both, the vacuum chamber and in the upleg snorkel, with nozzles diameters of 1 mm. This configurations obtained a kinetic constant of 0.00794 s⁻¹, circulation rate of 5.33 kg/s and the percentage of the plume area of 53.48%. For gas injection only in the upleg snorkel, the rate constant have the value of 0.00355 s⁻¹, circulation rate of 3.25 kg/s and the percentage of the plume area of 25.05%.

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0.00666 s\(^{-1}\), the circulation rate of 5.40 kg/s and the percentage of the plume area of 49.48%. By comparing these results, it is perceived that the plume area where the reaction takes place exerts a strong influence on the kinetic constant, even if the circulation rate is less. In contrast with the best result in the kinetic of decarburization, the worst result was obtained with the nozzles diameters of 2.2 mm in upleg snorkel with gas flow rate of 250 STP L/min and the nozzles diameters of 2.2 mm in vacuum chamber with gas flow rate of 250 STP L/min with circulation rate of 6.45 kg/s. This shows that the circulation flow rate has a limited influence, and the volumetric mass transfer coefficient is the main responsible for decarburization steel in RH degasser.

The results obtained in the present investigation contradict the common belief that increasing the melt circulation the melt circulation rate necessarily leads to faster decarburization.

A volumetric mass transfer coefficient was calculated based on the rate constant and on the circulation rate. The variation of the mass transfer coefficient with gas flow rates and nozzle configurations was very similar to that identified for the reaction rate constant. It was observed that the volumetric mass transfer coefficient presented a clear tendency to increase when the relative plume area in the vacuum chamber increased.

Acknowledgments

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Nomenclature

\[ V \]: Volume of water in the ladle (L)
\[ W \]: Mass of water in the ladle (kg)
\[ \Delta C \]: Variation of tracer concentration in the water (kg \cdot m\(^{-3}\))
\[ A \]: Area under the curve (kg \cdot m\(^{-3}\) \cdot s\(^{-1}\))
\[ K \]: Rate constant of the reaction (s\(^{-1}\))
\[ t \]: Time (s)
\[ C_{CO_2_{aq}} \]: Concentration of aqueous CO\(_2\) in the ladle (mol \cdot m\(^{-3}\))
\[ C_{CO_2_{aq}}^{eq} \]: Concentration of aqueous CO\(_2\) in the ladle in equilibrium (mol \cdot m\(^{-3}\))
\[ C_{CO_2_{aq}}^i \]: Initial concentration of aqueous C\(_2\)CO\(_2\) (mol \cdot m\(^{-3}\))
\[ a \cdot k \]: Volumetric mass transfer coefficient (m\(^3\) \cdot s\(^{-1}\))
\[ \rho \]: Water density (kg \cdot m\(^{-3}\))

REFERENCES


Appendix. Evaluation of the Effects of Gas Injection in the Vacuum Chamber of a RH Degasser on Melt Circulation and Decarburization Rates

Fig. A1. Results of the CO\(_2_{aq}\) concentration in the 3 positions of the pH sensor versus time.
Fig. A2. Results of the rate constant for the 3 positions versus time.