Original Article

The influence of flow asymmetry on refractory erosion in the vacuum chamber of a RH degasser

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ARTICLE INFO

Article history:
Received 13 February 2019
Accepted 22 June 2019
Available online 12 July 2019

Keywords:
RH degasser
Flow asymmetry
Refractory erosion
Modeling

ABSTRACT

Nozzle blockage in RH reactors is a serious operational problem since it can cause an asymmetric distribution of the steel flow in both the up-leg as well as the lower region of the vacuum chamber. This anomaly can alter the circulation rate in addition to affecting the erosion profile of the lower part of vacuum chamber refractory lining. In this study, the effect of nozzle obstruction on liquid circulation rate, wall shear stress, velocity profiles and flow pattern have been evaluated. In addition, refractory erosion in the vacuum chamber has been estimated through physical modeling and mathematical simulation results. Four blockage conditions were studied for different gas flow rates. There was a good agreement in physical and mathematical models results. Asymmetric flow was observed in vacuum chamber lower region in asymmetric blockage cases, which resulted in preferential wear on one chamber side in physical modeling experiments. The wall shear stress analysis in the vacuum chamber using a fluid dynamic model also indicates preferential erosion. When compared, refractory erosion results in physical modeling and shear stress in mathematical modeling presented good correlation.

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1. Introduction

Refractory wear costs involved in the production of steel represents a significant proportion of the overall manufacturing cost. Hence the choice of the most suitable refractory type for each application is of utmost importance, considering aspects such as resistance to high-temperature and to erosion. These not only depends on refractory type but also the fluid dynamic conditions of molten steel in contact with the refractory lining. In addition, the chemical properties of the slag and steel, atmosphere and temperature of process are factors that affect refractory linings. Hence the refractory structure zoning is important and the choice is made taking into account the physicochemical characteristics of the refractory and the environment to which it is exposed. Some aspects of predominant refractories used in metallurgy have been discussed in Ref. [1].
The RH reactor is widely used in secondary steel refining due to its flexibility in respect of metallurgical functions such as decarburization, degassing, homogenization, desulfurization, removal of nonmetallic inclusions and alloying additions [2]. The nozzle blockage is a recurrent problem in the RH and may directly influence the fluid behavior, especially in the vacuum chamber (VC). The uniform gas distribution and flow pattern gets altered, in case of asymmetric obstruction, and consequently, the circulation rate also is adversely affected [3–5].

The increase in liquid steel circulation rate is also related to the acceleration of refractory lining erosion. Among the possible refractory wear types, erosion is the most aggressive to the lining life, especially in the up and down legs as well as the VC lower region. The erosion is due to liquid steel and slag flow, which gradually removes the refractory bricks surface layer [6].

Evaluation of wall shear stress distribution, via mathematical modeling, helps to predict refractory lining erosion. The maximum shear stress point is the preferential point of wear [7]. Luo et al. [8] also used mathematical modeling, validated by simulations in a cold model, to calculate circulation rate and mixing time, as well as wall shear stress to predict preferential refractories wear in the RH reactor. The present work aims to analyze and characterize the influence of nozzle blockage, leading to asymmetric flow and its effect on circulation rate and refractory erosion.

### 2. Materials and methods

#### 2.1. Physical modeling

Fig. 1 gives the main dimensions of the RH reactor model, built in acrylic with a scale factor \( \lambda = 1.75 \). The dimensionless parameters, namely the Froude number \( (F_r) \) and flow \( (N_{Va}) \), serve as similarity criteria between prototype and physical model. The gas injection nozzles diameter was calculated by modified Froude number \( (F_{m}) \). A discussion of similarity criteria as applied to RH degasser can be found in Seshadri and Costa [9].

\[
F_r = \frac{V^2}{gD}; \quad N_{Va} = \frac{G}{D^2V}; \quad F_{m} = \frac{U^2 \rho_g}{D g \rho_l}
\]  

where \( V \) is liquid velocity; \( \rho_g \) and \( \rho_l \) are the density of the liquid and gas; \( D \) is the legs inner diameter; \( g \) is the gravity acceleration; \( U \) is the gas velocity in the nozzle and \( G \) is the gas flow rate in the nozzles.

For both the physical and mathematical simulations, a RH reactor model with 16 gas injection nozzles (2.4 mm internal diameter), distributed symmetrically in two rings have been considered. Four different conditions were studied, namely: Condition 1: no blockage; Condition 2: asymmetric blockage of 8 nozzles; Condition 3: asymmetric 4-nozzle blockage; Condition 4: symmetrical blockage of 8 nozzles. Fig. 2 shows the simulated blockage conditions.

#### 2.1.1. Circulation rate

The circulation rate in the RH degasser has been assessed by the conductimetry technique, as shown in previous studies [4,9–11]. It consists of injecting a pulse-shaped potassium chloride solution into the VC in the portion near the up-leg. A conductivity sensor was positioned in the down-leg for continuously measuring the salt concentration variation. Concentration values were evaluated by a data acquisition board connected to a computer, which stores and processes the data [4]. The circulation rate was computed using Eq. 2. The four clogging conditions were simulated for gas flow rates of 80,
90, 100, 110, 120, 140 L/min. The reported circulation rate is the average of 10 experiments.

\[ Q = \Delta C \cdot M_{\text{water}} / A_r \]  

(2)

where \( Q \) is the circulation rate (kg/s); \( \Delta C \) is the concentration variation in g of KCl/kg of water; \( M_{\text{water}} \) is the amount of liquid in the reactor in kg; \( A_r \) is the area of the region corresponding to the passage of the first tracer pulse under the concentration versus time curve (g of KCl/s/kg of water).

2.1.2. Flow profile pattern

To characterize the flow inside the VC, 200 ml of dye tracer, was injected 50 mm below the RH up-leg. A camera was positioned above the VC to visualize the chamber bottom. Frames were selected in order to evaluate and compare the dye scattering and path in the VC for the proposed blockage conditions. The conditions C1 and C3 for the 100 L/min gas flow were simulated.

2.1.3. Refractory erosion simulation in the vacuum chamber

Boric acid (7 g) pressed (3000 kgf) on metallic plates were used to simulate refractory erosion. Boric acid is soluble in water. As the water passes through the tablet surface, boric acid is gradually removed, which simulates the refractories erosion according to the technique proposed by Su et al. [12].

The region selected for this study was the lower portion of the VC, as it has a shorter refractory life if compared to other reactor regions [13]. In each experiment, 6 tablets were used (A–F), distributed symmetrically by the VC at a height of 3.5 cm (Fig. 1c). The tablets were weighed before and after the experiment to quantify the weight loss. Photos of each tablet were taken before the experiments to measure the area of the tablet's contact face with water which were measured and analyzed through the free software ImageJ. The results in terms of erosion rate (mm/min), was given according to Eq. 3.

\[ \text{Erosion Rate} = \Delta m / (\rho_b \cdot A_0 \cdot t) \]  

(3)

where \( \Delta m \) is the tablets mass change (g), \( \rho_b \) is the boric acid density (g/mm³); \( A_0 \) is the initial area (mm²) and \( t \) is the experimental time (min).

After tablets positioning into the VC, the test has been started, promoting liquid circulation between the VC and the ladle. The four blockage conditions to gas flow rates of 100 and 140 L/min were simulated. Three tests were performed for each flow rate. The time of each experiment was 2 min.

2.2. Mathematical modeling

The geometry used in the simulations was built using the software Design Modeler. Its dimensions are compatible with the physical model dimensions. The mesh independence study was performed by comparing the results of the circulation rate obtained with meshes of varied sizes. The mesh was constructed by the Meshing Modeler software, the mesh element sizing used was 18 mm in the lower vessel, 4 mm mesh in the up-leg and rest of the VC and 5 mm mesh in the down-leg. Therefore, the mesh was about 1 million elements and 413,000 grid points. The mathematical simulations were performed through CFX 18.2 software (Ansys®). In the mathematical model was assumed turbulent three-dimensional flow; incompressible Newtonian fluids (the expansion of the gas was disregarded); isothermal system (at 25 °C); ambient pressure equal to 1 atm and water and air standard physical properties at 25 °C. The turbulence model adopted was the \( k-\varepsilon \) model for the continuous phase (liquid), while for the discrete phase (gas), the dispersed phase zero equation model was adopted. It was assumed that the discrete phase had the same turbulent kinematic viscosity of the continuous phase [14]. The turbulence transfer between the phases was estimated by the Sato model [14].

The following conservation equations were solved: of mass conservation of each phase, namely, water and air; of volume considered that the volumetric fractions sum of air and water is equal to 1; of turbulent kinetic energy and the rate of dissipation of turbulence kinetic energy (model \( k-\varepsilon \)); of the momentum of each phase (turbulent form of the Navier–Stokes equations), in the three Cartesian coordinates (\( x, y \), and \( z \)). For more details see Peixoto et al. [10]. Based on Ref. [10], the Ishii–Zuber model was adopted for drag forces, which is more appropriate for high particle concentrations [14]; the model based on the Favre average (or mass-weighted average) was used to evaluate the drag force for the turbulent dispersion in situations of known values of turbulent dispersion coefficient \( C_{TM} \) [14] and for the wall lubrication force, Frank’s model has been used [10].

The boundary conditions applied to the problem are (see Fig. 1b) as follows. Non-slip condition applied to all walls, regions where the fluid has zero velocity. Injection condition: Gas is injected through nozzles (flow rates of 80, 90, 100, 110, 120 and 140 L/min) converted in mass flow rates (kg/s)). The selected flow regime is subsonic, with a turbulence intensity of 5% (average). Free slip condition on the ladle surface. VC surface: with 10 cm air layer-opening condition, with pressure equal to applied vacuum.

It is assumed that the gas bubble diameter is constant (the deformation, as well as the breaking and coalescence of the gas bubbles, are neglected). As in other contributions [7,8,11], the correlation given by Eq. 4 (adapted for ladle agitation with
gas [15], originally from Ref. [16]) is used to estimate the bubble diameter.

\[
d_b = 0.35 \left( \frac{G^2}{g} \right)^{0.2}
\]  

(4)

where \( G \) is the gas flow (Nm\(^3\)/s) and \( g \) is the gravity acceleration (m/s\(^2\)).

The mathematical simulation has been carried out in steady state conditions. The first order advection scheme (Upwind) was used to solve the proposed differential equations. To reduce residues fluctuation, the physical time scale control of 0.01 s and a maximum of 2100 iterations were used, which were divided into 300 iterations without turbulent dispersion force, 300 iterations after turbulent dispersion force insertion and 1500 iterations with advanced solution control option, coupled volumetric fraction. The convergence control was \( 10^{-5} \) (RMS, root mean square). This procedure follows Ref. [10].

Transient simulations were performed to evaluate the tracer dispersion in the VC. Tracer is represented by the Additional Variables function, using the volumetric scalar option (kg/m\(^3\)). The tracer injection point is shown in Fig. 1b, by Source Point tool, which is a source term simply added to a general scalar equation [14]. The steady-state flow field is then used in order to evaluate tracer dispersion. A transient simulation lasting 35 s is enough to describe the dispersion as it can be confirmed by physical model results.

3. Results and discussion

3.1. Circulation rate

Fig. 3 shows the circulation rate results for different gas flow rates in the physical and mathematical models.

It can be seen that, as the gas flow in the injector nozzles increases, the circulation rate also increases, which is in accordance with the results reported previously [4,17,18]. The circulation rate, in case of asymmetric blockages (C2 and C3), showed a considerable decrease relative to the condition without blockages (C1). In symmetric blockages condition (C4), there was no significant change in the circulation rate. These results are compatible with previous works [3-5]. There is good agreement between the experimental results and the values predicted by the CFD model. This supports the assumption that the mathematical model is able to predict the biphasic flow behavior in the RH reactor and could be used to evaluate other parameters, such as the wall shear stress of the reactor and correlate it with the refractories erosion rate.

3.2. Flow and velocity profile

The tracer flow pattern analysis as a function of time for the (C1) condition indicated symmetrical scattering by the VC. The tracer presented the tendency to flow along the VC side wall. The asymmetric 4-nozzle blockage (C3) presented preferential flow through one VC side. In this case, the tracer scattering occurred asymmetrically. The results obtained in the physical model experiments showed a good correlation with the results obtained through CFD, again supporting the mathematical model. Fig. 4 shows the tracer dispersion in the VC as a function of time for blockage conditions C1 and C3 via (a) physical model and (b) mathematical model.

The preferential flow along the wall can be explained by the higher velocity of the liquid phase in this region compared to the VC central region (Fig. 5). The liquid enters the VC at high speed, carried by the gas injected into the up-leg, and, as it spreads and gets in recirculation zones, loses speed. The liquid only regains speed in the impact region, the transition zone between VC and down-leg. Fig. 5 shows velocity vectors, calculated in the VC cross-section, at 3.5 cm height. Conditions C1 and C4 indicate a symmetrical distribution of the vectors. On the other hand, conditions C2 and C3 indicate higher velocity on one VC side, which explains the preferential flow. The symmetrical flow found for case C1 and the fluid scattering pattern by the VC are similar to the previous flow characterization results in the RH degasser [19–21].

3.3. Refractory erosion simulation in the vacuum chamber

Fig. 6 presents the average erosion rates of the boric acid tablets, positioned in the VC, for the 4 blockage conditions studied. Preferential erosion wear is noted on the tablets positioned close to the up-leg. In tablet A there was greater wear, while in D just above the down-leg, wear seems to be minimal. Under conditions C1 and C4, erosion rates between the Bänd Fäs as well as between Çând Etáblets were similar, which indicates flow symmetry in the chamber. In the cases C2 and C3, the results presented preferential wear of the Etáblets compared to F which suggests asymmetrical flow. A statistical hypothesis test confirm in general, the tablets average erosion in tests with 140 L/min was higher than in cases with 80 L/min, which may be related to the increase of the liquid local velocity.

The wall shear stress distribution in the VC has been evaluated through computer simulation for the different obstruction conditions (Fig. 7). At conditions C1 and C4, symmetry can be seen in the wall shear stress distribution in the VC, which signifies flow symmetry. In the cases C2 and C3, the shear stress deviation to one of the VC sides is detected, the higher shear stress is observed in the region correspondent to the point Bin the physical model. The wall shear stress distribution deviation indicates asymmetric flow in the VC. In all cases, the wall shear stress was higher in regions near the up-leg, due to the higher liquid velocity values, therefore, they are more susceptible to erosion degradation. The increase in the gas flow rate and, consequently, the local liquid velocity, increases the shear stress on the wall surface.

For analyzing the correlation between the erosion rate (physical simulations) and the wall shear stress in the VC, calculated via CFD in the regions shown in Fig. 1c, the position disregarded, due to the impact of air bubbles on the tablet’s surface, which increase the erosion rate in the physical model. For the other regions, the liquid phase is responsible for removing material from the tablets. It was
Fig. 3 – Circulation rate as a function of the gas flow rate for different obstruction conditions. (a) Physical model and (b) mathematical model.

Fig. 4 – Dispersion and trajectory of the tracer as a function of time for C1 and C3, gas flow of 100 L/min, via (a) physical model and (b) mathematical model.

Fig. 5 – Velocity vectors in the vacuum chamber cross-section, at the height of 3.5 cm for the blockage conditions (a) C1; (b) C2; (c) C3 and (d) C4.
found a good correlation between the parameters Wall Shear Stress and Erosion Rate (Eq. 5):

\[
\text{Wall Shear Stress (Pa)} = 5.47 \times \text{Erosion Rate (mm/min)} \times r^2 = 0.76(5)
\]

which validates the use of wall shear stress distribution analysis to predict preferential erosion wear points.

The distribution of wall shear stress of the up and down legs was analyzed (Fig. 8). The C1 and C4 cases showed symmetry in the stress distribution, which indicates symmetrical flow in both legs. On the other hand, the cases C2 and C3 presented an accumulation of stresses in the region opposite the nozzle blockages, which indicates a preferential flow of liquid on one side of the up-leg. The flow deviation is also indicated for down-leg. The up-leg presents higher levels of wall shear stress than the down-leg, since it is the momentum transfer region between gas and liquid bubbles. The C2 and C3 cases presented lower level of wall shear stress in the down-leg due to the lower circulation rate resulting from the obstruction.

The wall shear stress values shown in Fig. 8a are about one order of magnitude higher than the results reported in the work of Luo et al. [8], who performed a mathemat-
ical simulation of a physical model on a 1:5 scale. This difference is due to the fact that Luo et al. [8] worked with gas flows between 15 L/min and 35 L/min, much lower than the values adopted in this study, from 100 L/min to 140 L/min.

In industrial practice, the preferred wear points of the refractory lining are positioned in the impact zone, just above the down-leg, different from the result suggested by the wall shear stress analysis. This fact indicates that in addition to erosion, other wear phenomena may act in the region, such as the dissolution (MgO and Cr₂O₃ of the refractory), resulting from chemical reactions between refractory, slag and alloying elements (corrosion wear). The slag formed in function of the oxygen blow through a lance in a VC, like in RH-TOP process [22], is certainly unsaturated in respect of the main constituents of the refractory bricks, and extremely fluid, which should favor dissolution of some components of the refractory in the slag. Considering that this process at high temperatures (without kinetic restriction regarding the chemical reaction stage) is controlled by mass transfer, the mass transfer coefficient in the slag can be used to evaluate the dissolution potential. This is proportional to the relative refractory slag velocity if the interface renewal theory is adopted (Eq. 6) [23].

This way, one can relate the mass transfer rate with a velocity index (I) as given by Eq. 6, defined by the ratio of local velocity to the maximum velocity of the liquid in a predetermined region for the four conditions studied. While determining the velocity index in a shell in the VC located above the down-leg, 1 cm away from the wall (Fig. 9), it can be seen that, in cases C1 and C4, the point of maximum velocity index (region sensitive to greater mass transfer), is in the region of transition between the VC and the down-leg and is given by Eq. 7. In the C2 and C3 cases, the points of greatest value of I are shifted to the chamber side. For this analysis, the shell was selected only for half of the VC above the down-leg, as it is the region with the highest probability of contact between refractory and materials that cause its dissolution (FeO, slag, etc.).

\[ k = 2 \left( \frac{D_i v}{\pi L} \right) \]  \hspace{1cm} (6)

\[ I = \frac{v}{v_{max}} \]  \hspace{1cm} (7)

where \( k \) is the mass transfer coefficient; \( D_i \) is the diffusion coefficient of the constituents of the refractory in the slag; \( I \) is the liquid velocity index; \( L \) is the characteristic length and \( v \) is the liquid velocity, given by CFD results.

4. Conclusions

The refractory erosion in the vacuum chamber of the RH reactor was analyzed through physical and mathematical simulations. It can be concluded that:

- The circulation rate presented a significant decrease in cases of asymmetric blockages (C2 and C3) when compared to the case without blockage (C1);

- The tracer flow pattern for condition C1 indicated symmetrical scattering by the VC. However, C3 condition presented preferential flow through one side of the VC, indicating asymmetric flow. Both behaviors are reproduced by CFD calculations;

In the physical model, preferential erosion was noted on the tablet inserts positioned near the up-leg. Under conditions C1 and C4, erosion rates at symmetrical positions were similar as expected. In C2 and C3 cases, preferential wear of the tablets was observed on one side of the VC, resulting from the asymmetric flow;

The mathematical simulation, through wall shear stress, was able to predict points of higher erosion wear in the VC;

- It is suggested that above the down-leg, there is another wear mechanism acting, namely chemical attack of the refractory (corrosion). Thus, this is a critical point to the lining life of the RH reactor.

Fig. 8 – Wall shear stress of the up and down legs for the 100 L/min gas flow rate for the conditions (a) C1; (b) C2; (c) C3; (d) C4.

Fig. 9 – Liquid velocity index (I = v/v_{max}) to indicate preferred regions for corrosion wear in a shell above the down leg for conditions (a) C1; (b) C2; (c) C3 and (d) C4.
Acknowledgments

The authors wish to acknowledge the help provided by the research institutions in Brazil, namely CNPq, CAPES and FAPEMIG.

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