C-free Refractory for Reducing the Steel Ladle Energy Consumption: Numerical Analysis and In-situ Measurements

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Abstract

The energy consumption of steel ladles is closely related to the processing steps during the secondary refinement. Thermal energy from the liquid steel is lost when melting alloying elements, stirring gases or by natural heat transfer mechanisms. The refractory lining is responsible for approximately 70% of those energy losses, which will be dissipated to the environment while the ladle surfaces are being cooled. C-free refractories are microstructurally engineered to reduce the heat transfer in the material due to the lack of carbon (conducting phase) and the presence of lower thermal conductivity phases (i.e. microporous materials). The steel ladle process is a transient cycle that requires enhanced numerical tools to investigate the performance of such materials in specific conditions for each steelmaking shop. These tools were applied to estimate the saving energy potential of C-free refractories in a real case scenario (bottom and metal line) and the results showed a potential of reducing 20% the energy consumption. In-situ trials were also carried out and the reduction in the energy consumption was evaluated by comparing the liquid steel temperature for the different lining configurations. The expected benefits had good agreement with the tool predictions and the efficiency of such materials were validated.

1. Introduction

The scenario for the optimization of industrial processes has supported the application of new technologies and materials, as a consequence of trends on industrial modernization that aims to revolutionize the way society has been processing its goods. Basically, transformation industries have been looking for innovative ways of improving the efficiency in producing materials and the quality of the working environment, as many of these industries have safety as a priority. Also, they expect benefits by enhancing predictability and reducing the energy and material consumptions of their process [1].

In this study, a numerical model is applied to simulate the steel ladle process focusing on the refractory lining. The initial goal is to check the temperature accuracy between a model and real values. Good precision makes possible the investigation of other lining configurations and materials, to point out more efficient refractory solutions. For instance, the application of C-free refractory bricks and castables could reduce the energy consumption of steel ladles, provide new application techniques and improve the quality of the working environment, meeting few of the demands of the steel industry. The carbon in the refractory composition increases the effective thermal conductivity, resulting in higher energy losses and shell temperatures. Also, carbon containing refractories have been mainly shaped into bricks, due to limitations on processing such material in the presence of water.

After validation of the model, the application of C-free refractories in the lining of steel ladles was evaluated. Its potential benefits are highlighted considering the energy consumption associated with the thermal management of the secondary refinement and the safety associated to lower shell temperatures.

2. Material and Methods

2.1 Materials

Each material has a particular function in the steel ladle design (**Fig. 1**) and their properties have to attain the expectations. For instance, three main layers comprise the ladle lining: the working (WL) and safety layer (SL) and the steel shell. Occasionally, the SL can be divided in two material

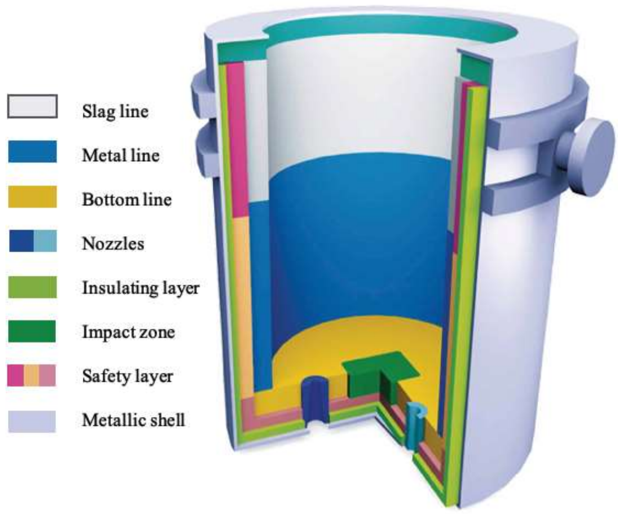

Fig. 1. Schematic configuration of the steel ladle lining [2].

sections: a dense refractory layer with low thermal conductivity and an insulating one. The metal and slag refractory lines (WL) are distinguished from each other to meet the requirements of the process and this is modeled to account the influence of the magnesia carbon bricks in the results. Nowadays, there is no equivalent commercial refractory to overcome the performance of MgO-C bricks applied in this region, but novel practices for reducing the carbon content can enhance their saving energy capability. Herein, both high and low carbon content MgO-C are investigated for the model validation and to evaluate the energy saving likelihood, respectively.

The C-free refractories are mainly designed for reducing the carbon pick-up during the steel processing, but they also have an advantage of presenting lower thermal conductivity at high temperatures. The impact of such property relates to the saving energy potential of the steel ladle, the shell and lining temperatures. This type of refractory is evaluated as a saving energy solution in the results section, when applying it on the metal and bottom lines of the ladle working layer.

2.2 Process

Each steel ladle step has a particular heat transfer condition and they are a simplification of the real process. In this study, the validation was carried out for two steel ladles in different stages. The first one was monitored just after relining (after 5 heats) and the second had been already in operation for 45 cycles. For both cases, only the waiting and holding steps were modeled as during the data collection no other step was featured.

The steel ladle process studied started while tapping in the BOF converter for pouring the molten steel. After that, several steps took place for the complete refinement and they differed according to the steel grade produced. If severe thermal corrections were carried out, they were considered in the model, i.e., aluminum and scrap additions. Afterwards, the steel ladle was placed in the continuous casting station to be drained out.

Later, the ladle started the waiting step and it was repaired and reheated when necessary. After full inspection, the ladle started another cycle and this went on successively. Due to the steel production schedule, the empty ladle might wait for long periods before the next heating or holding steps. It is important to emphasize that the time of each step and processes are also fundamental for the validation of the model.

2.3 Numerical model

The ladle geometry model was idealized as an open cylinder of revolution, considering six layers in the wall (working layer, mortar joint, two safety layers, insulating layer and metallic shell) and four layers in the bottom (working, safety and insulating layers and metallic shell). This lining concept was modeled to reproduce the ladle real configuration and to allow the investigation of other refractory materials with a low computational cost.

The analysis focused on the impacts of the refractory lining in the heat transfer and energy consumption of the process. The study aims to evaluate the C-free lining configuration regarding the temperature distribution and energy aspects. As a result, the target was to define the temperature *T(r,z,t)* for a radially symmetric heat transfer problem, governed by the differential equation (Equation 1). The transient solution enables the calculation of the heat flux for each time increment which can indicate the energy transferred between the model nodes, as stated below:

$$\rho(T)c_p(T)\dot{T} - \nabla \cdot [k(\dot{T})\nabla T] = 0 \qquad (1)$$

where ρ is the material density ($kg\ m^{-3}$), c_p the specific heat ($J\ kg^{-1}\ K^{-1}$) and k the thermal conductivity ($W\ m^{-1}\ K^{-1}$). The latent heat associated to material phase changes has not been considered. It is important to highlight that, when available, the material properties are temperature dependent. The transient heat transfer problem was solved numerically using Abaqus/CAE 6.14-1 finite element code. Details about initial and boundary conditions will be presented below.

Initial and boundary conditions

The steel ladle initial thermal state was considered after the vessel had undertaken six cycles, similarly as shown by Santos et al [3]. This generates an average temperature profile in the steel ladle lining, which can be used to overcome the previous and unknown temperature profile. After that, the boundary conditions (BC) are adjusted to assemble the real conditions of the monitored process and to validate the model.

The BC for the internal surfaces are applied according to each step of the process. During holding the molten steel, the convection heat transfer prevails on the ladle inner surfaces and Equation 2 defines the heat flux q_i associated with this phenomenon (convection boundary condition).

$$q_i = h_{steel}(T)(T_{steel} - T) \qquad (2)$$

where T_{steel} is the steel sink temperature far away from the internal surfaces – the initial value is the average tapping temperature obtained from the analyzed process, and h_{steel} is the heat transfer coefficient ($W\ m^{-2}\ K^{-1}$) for a simple steelmaking processing route[3], in which the molten steel loose heat basically by natural convection. Further, the amount of steel that the ladle holds up each heat influences the bath height, h_{steel} and the temperature drop rate [3]. These are the aspects that were taken into account for comparing the model results to the in-situ measurements. Note that the tapping and teeming steps were not modeled.

The BC in the external surfaces are the same during all ladle cycle steps, which are also similar to the internal surfaces during the waiting steps. In these cases, the surfaces are cooled via convective and radiative mechanisms [3].

2.4 Infrared images and analysis

Several infrared images of the shell and hot face were taken during the temperature measurements for the analyzed steel ladles. This was possible by using a FLIR T620 camera to produce the data set. The shell temperature was monitored for more than 24 hours for the two ladles. The hot face temperature could be measured only in some specific spots where one can capture the refractory working lining. Analyzing the data set, the average surface temperature was computed by applying masks, as shown in **Fig.2**.

2.5 Temperature drop and thermal additions

The energy consumption of the process can be estimated by the molten steel temperature drop. During the secondary refinement, if the temperature is lower than the required for the continuity of the process, aluminum and oxygen will be used to heat up the bath due to the energy released in the aluminothermic reaction. On the other hand, if the temperature is higher than expected, scrap additions will be made to reduce the molten steel temperature. The heat flux generated or removed from the bath (q_r) is converted to a temperature variation, which is then added to the molten steel average temperature T_{steel}. For that, the amount of steel and its thermal properties are considered in the balance.

The molten steel energy lost to the refractory lining is evaluated by integrating the heat flux with respect to the internal surfaces Γ, including the energy losses to the slag layer. The total energy loss is integrated to determine the molten steel temperature drop, for each time increment, as:

$$\frac{dT_{steel}}{dt} = \frac{1}{\rho_{steel} c_{steel} V}\left(-\int_{\Gamma} q_i d\Gamma + q_r\right) \qquad (3)$$

where T_{steel} is the molten steel density (7000 $kg\ m^{-3}$) and c_{steel} the specific heat (627 $J\ kg^{-1}\ K^{-1}$).

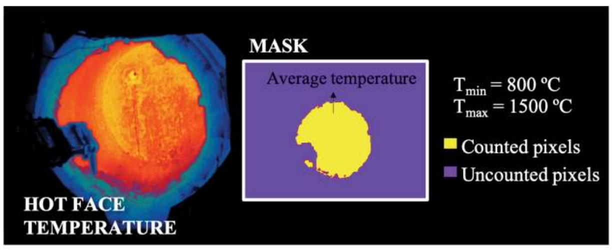

Fig. 2. Example of infrared temperature analysis for the steel ladle waiting step. Different masks and ranges were applied to determine the average temperature in each region (shell and hot face).

3. Results and discussion

The results are presented in two sections. The first is the model validation, accounting for the internal and external surfaces, and for the molten steel temperature comparison. The second section highlights the benefits of the application of the C-free lining in the thermal management and energy consumption of the steelmaking process.

Validation

The simulation of industrial processing requires the development of numerical modeling tools. This is essential for the investigation of different refractory lining and for estimating the benefits associated to its optimization.

Firstly, the average shell temperature was analyzed. The average mask values are plotted in **Fig. 3** for each cycle time (A), clearly showing that there is a significant deviation in the values. That is because the images captured the shell average temperature from many different spots in the steelmaking shop. Sometimes, the full view of the metallic shell is not possible, as for example while the ladle is in the continuous casting machine (CCM). These events are responsible to deviate the average values due to the temperature changes according to each ladle region (bottom, middle and top) [3]. The model average shell temperature shows a much more regular behavior because it would be similar to a thermocouple placed in a fixed position. In general, the comparison between in-situ

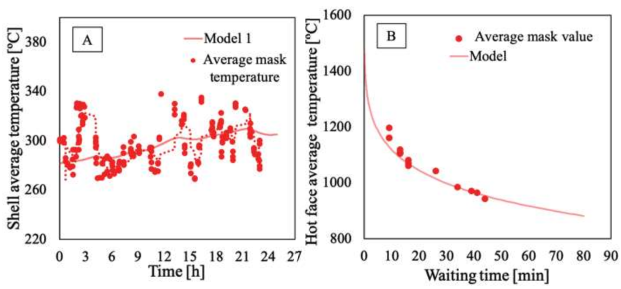

Fig. 3. Average shell temperature for all steel ladle cycles (A) and average hot face temperature for one of the cycles (B). The values from model and in-situ measurements are compared and the results show good approximation.

measurements and the model showed good agreement.

Also, **Fig. 3** presents the hot face temperature comparison. Only one of the several waiting steps is taken as an example for the same steel ladle. There are less measurements and no continuous set of data, due to the fewer moments when the hot face is exposed and its infrared image can be captured (the best moment is while the ladle is repairing). The model and average mask values for the hot face temperature showed good similarity, for most of the analyzed waiting steps.

Fig. 4 shows the molten steel temperature comparison between simulation (continuous line) and in-situ measurements (dotted line). The comparison is made for a less complex processing route of the steel ladle, in which the secondary refinement occurs only at the ladle treatment station (LTS). This case has a better analogous heat transfer conditions between the model and the process. Although, several heats were analyzed and in general the model predicted higher temperatures than the data obtained in-situ. This is expected as the heat losses considered when modeling are less intense compared to the real process. In general, the model is an efficient tool for predictions of the process, specially when aiming the analysis of different refractory lining under the same condition.

Solution

The C-free lining benefits are presented in **Fig. 5**. The first case shows that if the heat conditions are maintained, the lining solution would imply a higher average steel temperature, 16 ºC. This impacts directly on the amount of energy need for adjusting the bath temperature whenever it is out of the target.

Further, the lower energy losses would usually reduce the energy input at the beginning of the ladle cycle. For instance, this solution could reduce the tapping temperature of the BOF with the same benefit, 16 ºC. Lower tapping temperatures also implicates in better operational conditions in the BOF (reducing the refractory wear), and in the steel ladle (less corrosion, energy losses, etc.).

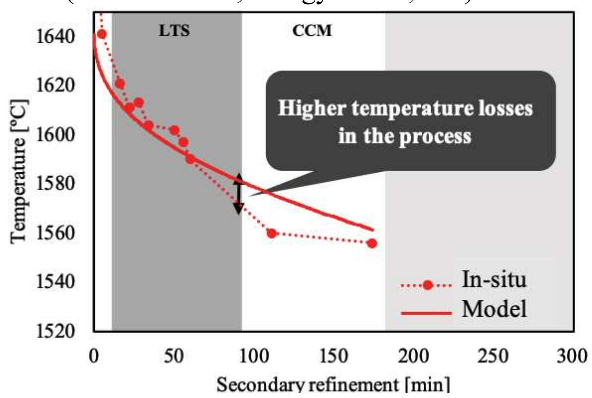

Fig. 4. Average steel temperature comparison during the secondary refinement.

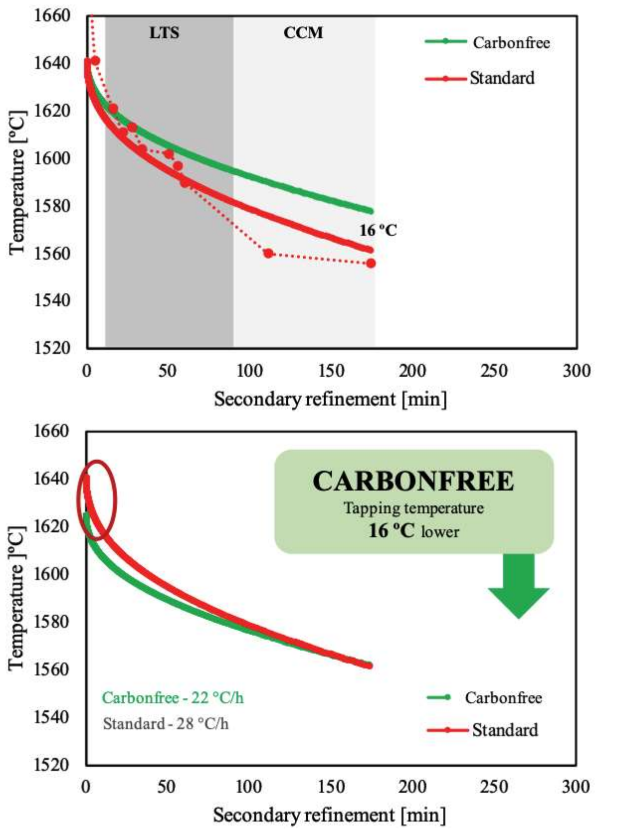

Fig. 5. Solution investigated for the C-free refractories applied as the working layer. The reduction in the molten steel temperature drop accounts for 20% which is also related to the saving energy potential.

4. Conclusion

Numerical analysis is a powerful tool for investigating the benefits of refractory solutions. The thermal management tool for the steel ladle lining was validated and it can point out energy saving benefits for different refractory materials. For this case, the application of C-free linings in steel ladles reported a saving energy potential of 16 ºC in a general cycle condition, which can impact significantly in the optimization of the process (reduced tapping temperatures or lower aluminum consumption).

5. Acknowledgments

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