STEEL LADLE ENERGY SAVING BY REFRACTORY LINING DESING

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ABSTRACT

The secondary metallurgy is a high energy-intensive step in steelmaking process as it requires an accurate match of the composition and temperature of the molten metal during the ladle refining. In this context, the steel ladle lining plays an important role on the energy consumption of the process, as the refractory thermal properties are strictly related to the ladle ability to keep constant the molten metal temperature. Aiming to improve the energy efficiency, reducing both costs and the environmental impacts, distinct working layer materials and the presence of an insulating one was considered and investigated. The molten steel energy losses were determined by the average heat flux in the lining hot face during holding the liquid steel and they were compared to evaluate the energy efficiency of different lining configurations. The simulation results indicated that the configurations containing an insulating layer significantly reduced the energy losses from the molten metal. The distinct refractory working layer materials also had a great impact in the energy consumption of the process due to their different thermal conductivity and heat capacity. In summary, saving energy in steelmaking is a key factor to improve the process efficiency and, when supported by a thermal and energy balance tool, new materials and optimized lining configurations could be explored, leading to a higher performance of the steel plants.

Key words: steel ladle, refractory, saving energy, simulation, optimization

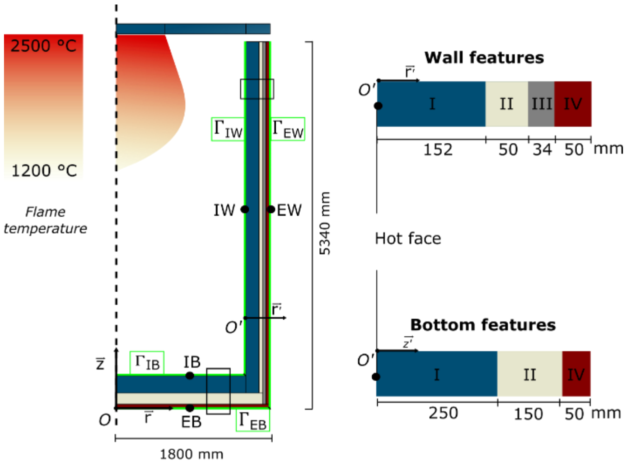
INTRODUCTION

The industries that carry out high temperature processes, e.g. the iron and steel industry, require advanced energy solutions for efficiently heat management during their processing. Steel makers have been looking for new strategies and solutions to decrease the energy consumption, due to the growing demands for steel products and the reduction in the environment impacts. In steelmaking, most of the green solutions will depend on the proper design of the refractory linings in all furnaces and machinery, suppressing the molten metal heat losses and reducing the specific refractory consumption per ton of steel. Also, controlling and monitoring the thermal state of the process is essential to ensure the final product quality and to guarantee the steel mill operational flow [1, 2].

Hence, the determination of an optimum thermal condition of each process step can lead to environmental-friendly solutions, when considering the tailored application of refractories and insulating materials [3, 4, 5, 6].

Notably, steel ladles play an important role in steelmaking and its optimization requires understanding the thermal state of each process step [1]. The ladle runs cyclically and its operational steps can be classified in two categories: empty ladle and full ladle (holding molten steel). In each one, different physical and chemical phenomena act and need to be considered as they significantly affect the ladle thermal state. For each cycle, the estimated energy consumption is defined according to the amount of heat lost by the molten steel during holding (considering the extra energy required to recover these heat losses) and the amount of fuel burned on the heating steps.

Analytical [1, 2] and numerical models [3, 4, 7] have been investigated by various authors, in order to understand the ladle thermal state condition and how energy is being transferred during the ladle operational cycle. These approaches aim to represent the process physical features and support the energy consumption analysis for distinct refractory linings. Suitable modeling of the steel ladle can also point out the temperature on the metallic shell that affects its service life and the quality of the working environment. Moreover, the models can highlight which



Configuration

Layer	I	II	III	IV
1	Material A	Material C	Material C	Material E
2	Material A	Material C	Material D	Material E
3	Material B	Material C	Material C	Material E
4	Material B	Material C	Material D	Material E

Fig. 1 Ladle configuration features: geometry, flame temperature and material locations. Bottom (B) and wall (W) details show the thickness and materials of each layer, determining four ladle designs. The combination of two distinct WL refractories (layer I) and the presence of an insulating layer (layer III) results in four ladle configurations, as shown inset. The position of the points of interest: IW, EW, IB and EB are defined. The surfaces Γ_{EW}, Γ_{EB}, Γ_{IW}, Γ_{IB}.are highlighted in green because the boundary conditions and results are related to these regions.

ladle configuration would be more sensitive to thermal shock [8], whose implications would decrease the refractories service life. Besides that, only numerical simulation modeling enables the evaluation of complex geometries in a variety of conditions, overcoming the limitations of the analytical modeling and guiding the development of optimized solutions.

In the present study, an axisymmetric finite element model was developed to evaluate different refractory lining configurations according to the steel ladle energy consumption. Additionally, other features are discussed, as the shell and working lining temperatures that also affect the process optimization. The proposed model enables the determination of the temperature profile and the energy transfer in the ladle during cycling. In particular, the determination of the amount of heat lost from the molten steel to the lining is highlighted. The model is applied to simulate six ladle cycles, in fully transient state, as the materials properties and ladle dimensions can be assumed constant. However, such analysis can provide meaningful results to what has been proposed. The different linings have been evaluated considering the presence of an insulating layer and the

Steps		Step time: 1st cycle	Step time: 2nd - 6 th cycle
S1	Heating	6h00	2h00
S2	Waiting 1	1h00	1h00
S3	Holding	1h30	1h30
S4	Waiting 2	1h00	1h30

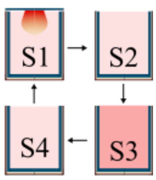


Fig. 2 Simplified description of the modeled ladle cycle. The four steps: pre-heating (or reheating), waiting 1, holding and waiting 2 represents the operational process considered. The inset table shows the time for each step and cycle.

use of two materials with distinct thermal properties in the working layer, resulting in of four lining configurations that were analyzed based on multiple criteria analysis (energy consumption, shell temperature and working lining temperature before tapping).

MATERIALS AND METHODS

Materials

The steel ladle lining consists of different materials layers in order to meet specific mechanical and thermal requirements, leading to the complex architecture presented in Fig. 1. Each material has a particular function in the ladle design and its properties are significantly different, as presented in Tab. 1. For instance, three main layers comprise the ladle lining: the working (WL) and permanent layer (PL) and the steel shell. Occasionally, the permanent layer can be divided in two material sections: a dense refractory layer with low thermal conductivity and an insulating one. In the study, the selected materials and configurations are expected to enhance the effectiveness of the analysis, even though they may represent a specific and non-usual condition. Furthermore, the metal and slag refractory lines had no distinction in the working layer, because the model have neglected any thermochemical phenomena, as wear or corrosion, that would require distinct WL materials.

The detailed physical phenomena of each step and the FEM considerations will be described in Section 2.3.

The materials applied in the steel ladle are exposed to a wide range of temperature. Depending on that, they might have a specific behavior and properties. Hence, the materials characterization in the operational temperature range is very relevant to obtain an accurate numerical model. The properties shown in Tab. 1 were obtained from the literature.

Process

The studied ladle geometry comprises two concentric cylinders (Fig. 1) and each step has a particular heat transfer condition. Hence, four steps are modelled: pre-heating (reheating), waiting 1, holding and waiting 2, in order to set a representative view of the ladle cycle (Fig. 2).

After the refractory lining installation on the metallic shell, the ladle is dried and pre-heated, reaching the ideal lining thermal condition. Natural gas burners are the most common heating source and their oxygen and gas flow rate are controlled [9] to guarantee an ideal combustion and flame temperature. If the ladle is not properly pre-heated, it will demand extra energy consumption during processing, due to higher temperature changes in the molten steel. Also, WL severe temperature variation can downgrade the refractory erosion resistance. For this reason, the pre-heating energy consumption cannot be avoided, even though the energy efficiency of the step can be significantly improved, e.g., applying a high emissivity coating on the refractories surface. After pre-heating, the ladle is conveyed to the LD converter or the electric arc furnace for holding the molten steel. At this moment, several processes take place for the complete refinement and they vary according to steel shops and the steel grade produced. Afterwards, the ladle is placed in the continuous casting station to be drained out (teeming). Later, the ladle is repaired and reheated when necessary. After full inspection, the ladle starts another cycle and it goes successively. Due to the steel production schedule, the empty ladle might wait before the next heating and holding steps.

Numerical model

The steel ladle has a complex geometry - lifting points, structural reinforcements, valves, etc. – however, when generating the ladle model, these detailed features were neglected to reduce the computational cost, as the analysis focused on the impacts of the refractory linings in the heat transfer and energy consumption of the process. Herein, the ladle structure model was idealized as an open cylinder of revolution, considering three or

Tab. 1 Typical steel ladle materials and its properties. In addition, each material is identified by chemical composition, usual application shape, labeling and lining layer. All references are presented.

Material	Property	Unit	Temperature [°C]	Value	Source
$MgO\text{-}Al_2O_3$ Brick Material A Working lining	ρ	$kg\ m^{-3}$	-	3210	
	k	$W\ m^{-1}\ K^{-1}$	400	4.65	
			700	3.49	
			1000	4.65	
			1300	5.81	
	c_p	$J\ kg^{-1}\ K^{-1}$	-	1090	
	ε	-	-	0.9	
MgO-C (20% wt) Brick Material B Working lining	ρ	$kg\ m^{-3}$	-	2805	
	k	$W\ m^{-1}\ K^{-1}$	300	26.0	
			700	23.0	
			1200	21.0	
	c_p	$J\ kg^{-1}\ K^{-1}$	200	980	
			700	1240	
			1200	1360	
	ε	-	-	0.8	
High Alumina Brick Material C Permanent lining	ρ	$kg\ m^{-3}$	-	2660	
	k	$W\ m^{-1}\ K^{-1}$	400	2.60	
			800	2.10	[10]
			1200	2.00	
	c_p	$J\ kg^{-1}\ K^{-1}$	200	890	
			700	1060	
			1200	1144	
Alumina insulator Fiber plate Material D Insulating layer	ρ	$kg\ m^{-3}$	-	510	
	k	$W\ m^{-1}\ K^{-1}$	250	0.15	
			800	0.25	
			1350	0.34	
	c_p	$J\ kg^{-1}\ K^{-1}$	-	1047	
Carbon steel Plates Material E Shell	ρ	$kg\ m^{-3}$	-	7840	
	k	$W\ m^{-1}\ K^{-1}$	200	47.34	
			350	42.34	
			500	37.35	
	c_p	$J\ kg^{-1}\ K^{-1}$	200	529.8	
			350	538.7	
			500	666.5	
	ε	-	-	0.6	

four layers in the wall and three layers in the bottom. This model aims to evaluate different configurations regarding the temperature distribution and energy aspects. As a result, the target was define the temperature $T(r,z,t)$ for a radially symmetric heat transfer problem, governed by the heat transfer 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 and shown in Tab. 1. 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 is considered at room temperature at the beginning of the analysis (first cycle), i.e.:

$$T(r, z, t = 0) = T_0 = 40\ °C \qquad (2)$$

Boundary conditions (BC) are applied in the internal (Γ_{IW} and Γ_{IB}) and external (Γ_{EW} and Γ_{EB}) model surfaces which are

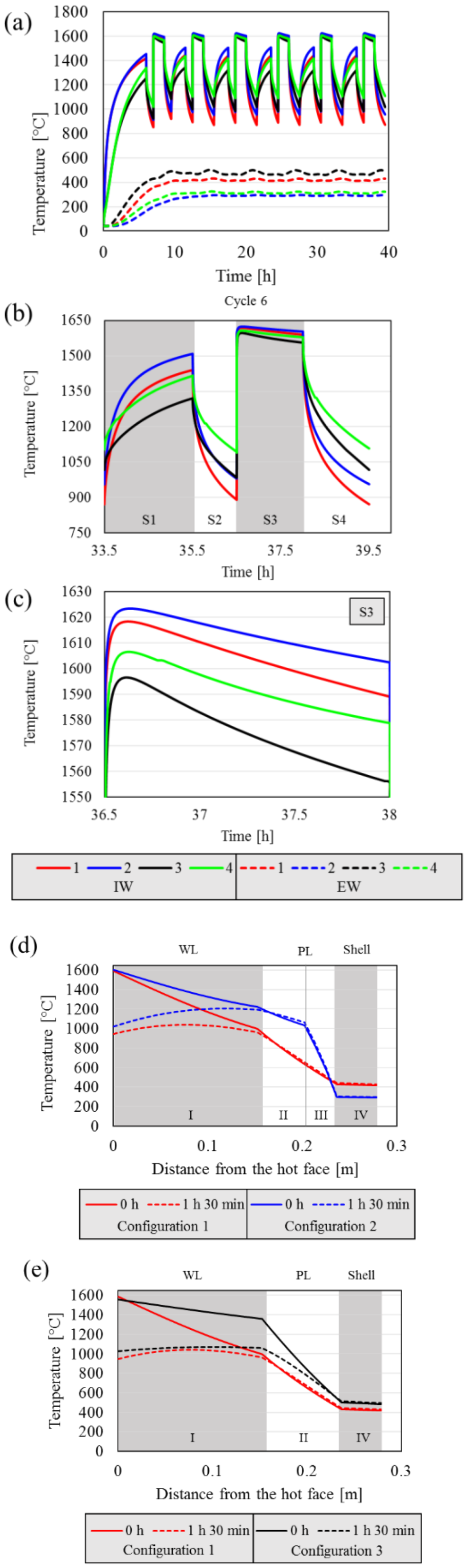


Fig. 3 (a) Temperature evaluation for the internal and external wall points (IW and EW) for configurations 1 to 4, (b) detailed WL temperature profile of the sixth cycle and (c) the holding step (S3) temperature evolution. The temperature profiles along the ladle wall, from point IW (hot face) to EW (cold face), at the beginning of S4 (solid lines) and at the end of this step (dashed lines) for the ladle sixth cycle. Figure 5 (d) shows the insulating layer effect and the right plot (e) shows the WL material effect in the lining temperature

identified in Fig. 1. The BC in the external surfaces are the same during all ladle cycle steps and they are related to the heat transfer via convective and radiative mechanisms. Therefore, Equation 3 expresses the BC for all external surfaces which is given by the heat flux q_e as:

$$q_e = h_{air}(T)\left(T_{env} - T|_{\Gamma_e}\right) + \sigma\varepsilon(T)\left(T_{env}^4 - T^4|_{\Gamma_e}\right) \quad (3)$$

where, h_{air} is the heat transfer coefficient ($W\ m^{-2}\ K^{-1}$) on the external surface Γ_e, σ the Stefan Boltzmann constant (σ = $5.6697 \cdot 10^{-8}\ W\ m^{-2}\ K^{-4}$), ε the emissivity and T_{env} the environment temperature (40 °C).

The BC for the internal surfaces are applied according to each process step. During pre-heating and reheating steps, the internal surfaces are heated up mainly by radiation mechanisms (Equation 3). Nevertheless, for the holding step, the convection heat transfer on the ladle interior is dominant and the numerical boundary condition is expressed by Equation 4.

$$q_i = h_{steel}(T)\left(T_{steel} - T|_{\Gamma_i}\right) \quad (4)$$

where, T_{steel} is the steel sink temperature far away from the internal surfaces Γ_i, h_{steel} is the heat transfer coefficient ($W\ m^{-2}\ K^{-1}$) on the internal surface Γ_i and T_{steel} is the molten steel initial temperature (1650 °C). For waiting 1 and 2 steps, the BC on the internal walls are similar to the heating one but without the heat source, consequently, cooling the internal surfaces via radiative heat transfer. During all steps where the steel ladle is empty (pre-heating, reheating and waiting 1 and 2), the radiative heat transfer is modeled as an open cavity radiation (room temperature = 40 °C).

Energy evaluation

The energy consumption of the process can be computed based on the amount of energy that enters or exits the system through the internal and external model surfaces. The energy is evaluated by integrating the heat flux with respect to time and Γ, such as the energy at instant t, $E(t)$ is given by:

$$E(t) = \int_0^t \int_\Gamma q(r, z, t)\, d\Gamma\, dt \quad (5)$$

where, $\Gamma = \Gamma_{EW} \cup \Gamma_{EB} \cup \Gamma_{IW} \cup \Gamma_{IB}$. It is important to highlight that no heat exchanges are considered from top surfaces, so its share to the energy quantification was neglected.

RESULTS AND DISCUSSION

The temperature evolution was evaluated in four points identified in Fig. 1: internal wall (IW), internal bottom (IB), external wall (EW), and external bottom (EB). The selected points provided an overview of the ladle surface temperature history.

Fig. 3 (a) shows the temperature history for the internal and external wall (IW and EW) to compare the four lining configurations presented in Fig. 1. Fig. 3 (b) clearly shows how the working lining temperature evolves during the sixth cycle. The other inset (Fig. 3 (c)) shows the holding step in detail, where

Tab. 2 Comparative table analysis (4 configurations).

		1	2	3	4
Energy consumption [MWh]		3.55	0.00	14.71	8.11
Average temperature [°C]	Environment	40.0			
	EW Shell	389.0	262.5	447.6	289.9
Average temperature [°C]	Liquid steel	1650.0			
	IW Working lining	884.3	967.5	977.4	1081.3

IW temperature can be directly related to the liquid steel energy losses.

At heating, IW temperature is higher for the low thermal conductivity WL material (configuration 1 and 2) and the presence of an insulating layer also increase the lining temperatures (configuration 2). The first reason is that the WL material with lower thermal conductivity increases the availability of thermal energy to be used for heating up the refractory volume close to the hot face, as only a small amount of energy is being transferred to external regions (Equation 1). Higher hot face temperature decreases the heat transfer between the lining and the flame, as the radiative heat transfer is proportional to temperature difference between the flame and IW. Secondly, the presence of an insulating layer (configuration 2) minimizes the temperature gradient in the permanent and working ones (Fig. 3 (d)), reducing the driving force for thermal conduction which increases the surface Γ_{IB} and Γ_{IW} temperatures (more heat stored in the lining).

At waiting steps S2 and S4, configurations 3 and 4 led to higher heat propagation to the lining volume, due to the higher thermal conductivity of material B. This energy is stored and compensates the energy losses through Γ_{IW}, keeping the surface temperatures higher after the waiting step is completed (end of S4). The presence of an insulating layer increases even more the surface temperatures.

Fig. 3 (d) and (e) show the steel ladle temperature profile at different times: 38h00 and 39h30, respectively, at the beginning (solid lines) and end (dashed lines) of waiting 2 for cycle 6. The insulating layer directly affects the temperature profile, as can be seen in Fig. 3 (d). Configuration 2 shows the higher energy stored in the working and permanent layer, which matches with its higher lining temperature after 1 h and 30 min. The profiles in the (e) plot show the WL material thermal conductivity effect in the lining stored energy; being higher for configuration 3 when compared to configuration 1, which compensates the energy losses and agrees with what was stated before.

Moreover, considering the shell temperature EW shown in Fig. 3 (a) and (b), it can be seen that configuration 1 (material A) has a lower average shell temperature than configuration 3 (about 50 °C lower), when the shell surface Γ_{EW} is in quasi steady regime. The insulating layer decreases the shell temperature in 130 °C for configuration 1 to 2 and 170 °C for configuration 3 to 4.

Such thermal analysis allows the calculation of the energy losses to the environment, which is related to the heat flux on the shell and working lining surfaces. This analysis helps to understand the function of each material during cycling. As mentioned before, the global performance of the refractory design can be evaluated by the energy quantification during the entire process (Equation 5).

Fig. 4 shows the total heat losses from the molten metal to the investigated refractory configurations, after six cycles. Assuming that the top surfaces are adiabatic, configuration 2 shows the lowest metal energy losses and, compared to the others, it would have the lowest energy consumption (Tab. 2), used to eventually reheat the molten bath. This is a consequence of the low thermal conductivity WL brick and the presence of the insulating layer. Configuration 3 and 4 absorb more energy, because the higher thermal conductivity of material B increases the heat transfer to the lining and the thermal energy can be stored in a larger volume. Considering that the acceptable amount of heat losses is equal to that presented by configuration 2 (20.83 MWh), Tab. 2 shows that the energy consumption to recover the temperature drop of the bath would be 3.55, 0.00, 14.71 and 8.11 MWh, for configurations 1, 2, 3 and 4.

CONCLUSION

- The analysis considered four different steps for each cycle, accounting the heat losses when the ladle is empty, holding the molten metal or being heated. This global approach led to a better understanding of the ladle thermal condition and more possibilities for the process optimization.
- The model computed the temperature profile and the energy transfer for each step period and the ladle surface. It also considered the thermal properties changing regarding to the temperatures. Based on that, the evaluation of the refractory lining configuration was carried out according to energy consumption, working lining temperature variation and shell average temperature.
- The presence of an insulating layer resulted in the reduction on the energy consumption, lower shell temperatures and working lining temperature changes.
- The low conductivity working lining material showed a better performance on saving energy and reducing the shell temperature, but the temperature variations of the working lining were higher. Configuration 2 showed the highest global energy efficiency, because it combines the WL material of low thermal conductivity and the insulation layer.

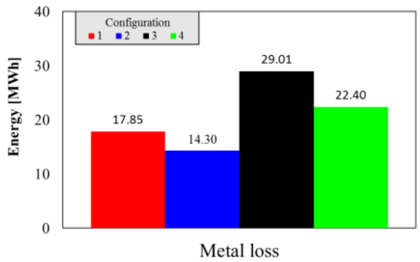


Fig. 4 Liquid steel energy loss to the lining after six cycles.

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