ORIGINAL ARTICLE

Holistic view of the insulating layer on the thermal efficiency of a steel ladle lining

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Abstract

The lining design of steel ladles has a major impact on the performance of these metallurgical vessels. For instance, their better thermal performance is mainly related to the refractory materials applied in the lining, which requires continuous quality and cost optimizations. In this study, different refractory linings were investigated in order to understand their effect on the thermal performance of the steel ladle, that is, on the control of the average steel and shell temperatures, effect on the amount of stored energy in the refractory lining and on the cycling energy consumption. The influence of distinct configurations of insulating materials (position, thickness, and types) on those parameters was investigated by heat transfer simulations using numerical tools. The results pointed out the insulating materials efficiency on reducing the shell temperatures and increasing the average steel temperature. However, the benefits of applying the insulator with thicknesses over 21 mm or applying it at the bottom are less significant. The application of the foam insulator at unusual positions showed promising results, such as between the safety and working layer and at the hot face. The former position enhanced the performance during pre-heating whereas the latter significantly increased the steel temperature (34°C). Consequently, the study pointed out new designs for the project of steel ladle linings, improving their efficiency, targeting solutions for saving energy, and reducing the environmental impacts.

KEYWORDS

saving energy, steel ladle, refractory lining design, insulating layer, heat transfer modeling

1 | Introduction

Currently, one of the greatest world challenges is the increasing demand for clean and renewable energy sources in order to avoid high CO_2 emissions from burning fossil fuels.[1] However, saving energy practices have also been an alternative solution for decreasing the energy demand, without impairing the quality of people's life or the economic and technological development of our society.

Industries have always looked for those practices, as they consume over 50% of all produced energy according to the U.S. Energy Information Administration.[2] Hence, steel,

cement, glass, and ceramic industries operating high temperature processes account for the largest shares of the total industry energy consumption. Because of that, they are constantly searching for technological solutions and more efficient materials to save energy, reduce costs, and minimize environmental impacts.[3]

Thermal insulating materials are always applied whenever there is a need to reduce the heat transfer and energy consumption. In steel plants, for instance, they are used in the refractory lining design of several pieces of equipment, such as the electric arc furnace, steel ladle, and RH degasser, to reduce energy consumption and shell temperatures (improving the quality and safety of the working environment).[4,5] Such thermal insulating materials are refractory ceramics designed to act as a thermal barrier for high temperature processes, decreasing the heat flux generated by the temperature gradient between the inner part of the equipment and the environment.

Based on that, the effective or total thermal conductivity (k_{ef}) of the insulator needs to be defined to account for the share of each heat transfer mechanism: conduction (k_{cond}), convection (k_{conv}), and radiation (k_{rad}).[6,7] Low k_{ef} values depend on the microstructure and composition of the insulating material, which should also guarantee mechanical strength and thermal shock resistance.

Nowadays, most of the high temperature thermal insulators available on the market comprise alumina and silica fibers or particulates, and their microstructures depend on different processing methods. The insulators containing ceramic fibers present very low thermal conductivity due to the high porosity of the fiber entanglement. Commonly, when blanket shaped, these materials are used at the cold face of metallurgical furnaces (between the dense refractories and metallic shell). When molded into rigid plates, they are applied at the hot face of conventional high-temperature furnaces (no corrosive environments). The thermal conductivity and stability of fiber insulators depend on the environmental conditions and their high sensitivity to the pressure that could compress the fiber structure and increase the contact points among the filaments, therefore increasing the effective thermal conductivity. Furthermore, the pores in their microstructure are large enough for heat transfer by radiation at high temperatures, and lastly, they might present drawbacks related to high toxicity.[8] Hence, the application of fiberless insulators (ceramic foams) has been investigated and high-performance insulating materials using advanced methods, and microstructure simulation have been studied.[9] These latter insulators present low and stable thermal conductivity even at high temperatures (1,000°C), nontoxic processing routes and also the likelihood of being applied in more aggressive environments (hot face of metallurgical vessels).[10,11] On the other hand, the efficiency and durability of all insulators strongly depend on the mechanical, chemical, and thermal solicitations during use, as most of the failures are related to cracks associated to thermal shock, compressive loads, and very corrosive environments.[12] In the steel industry, several installations have used insulating materials because of their benefits, such as for steel ladles.

Steel ladles are used to convey the molten steel from converters or electric arc furnaces to continuous casting machines. They are also used as a versatile reactor for homogenization, deoxidation, desulphurization, chemical and temperature adjustments of steel grades.[13] According to Lopes,[13] the application of thermal insulators between the safety layer and the shell (standard position) reduces the external temperature of the equipment, decreasing the energy losses to the environment and reducing the molten steel temperature drop during the secondary refinement. Liu et al[14] and Li et al[15] evaluated the insulator's benefits on the shell temperatures of a torpedo car and a steel ladle, respectively. Rahm[16] also showed the advantages of insulating ladle lids which provides lower operational costs as it increases the energy savings and the life of the refractory lining.

The importance of evaluating the thermal behavior of steel ladles is required for the precise control of the steel temperature and the operational conditions of the refractory lining.[17] It also helps to find saving energy solutions, reduce materials consumption, improve productivity, and scale down environmental impacts.

However, there is a lack of studies in the literature exploring the specific effects of different configurations of insulating materials, such as its thickness, lining position, or type (foam, fiber, etc.) on the steel ladle thermal state. Therefore, the present work proposes using a computational tool to estimate the energy and thermal profile of several lining configurations, which are compared to elucidate all relevant effects, as reported in.[17] The temperature gradient and energy consumption are calculated by modeling the ladle process via the finite element method (FEM). The model domain consists of the refractory lining (simplified) and the shell, whose contours assume boundary conditions close to the heat transfer phenomena acting in each step of the process. All heat transfer mechanisms (conduction, convection, and radiation) are considered to represent the ladle cycle. In this study, the ladle lining was represented as an axisymmetric geometry and its cycle was illustrated into four main steps.[17] The analyzed cases considered several lining configurations related to position, thickness, and type of thermal insulator. The ladle lining was also analyzed with a thinner working layer (representing a half-campaign scenario), assuming that the lining would have operated for approximately 60 cycles. The results highlighted the temperature and the heat flux in the refractory system, thus defining the amount of energy required in the process, as well as the likelihood for optimized configurations.

2 | METHODOLOGY

2.1 | Materials

Steel ladles are generally designed using three layers of different materials: the working and safety ones comprising refractory materials with high to medium thermal conductivities, good mechanical properties and corrosion resistance at high temperatures, and the metallic shell that yields structural resistance to the ladle. The lining can also have an additional insulating layer, which is the object of study of the present work.

In the present case, the working and safety layer are composed of an alumina-magnesia refractory (> 85%wt Al_2O_3—Material 1) and a high-alumina refractory (> 70%wt Al_2O_3—Material 2), respectively, and the shell is made of a low-carbon steel (Material 6). These materials are usually applied in steel ladles, and their thermal properties (thermal conductivity and specific heat), density, and emissivity are shown in Table 1. The thermal conductivity of the refractory bricks was experimentally measured by the hot parallel wire, according to ISO 8894-2,[18] including the foamed insulator, identified as Material 3. The other insulating materials (Material 4 and Material 5) had their thermal conductivity

TABLE 1 Material properties considered in this study. Their general chemical class, usual application shape, producer, and lining location are presented

Materials		Density (kg m^{-3})	Thermal conductivity (W m^{-1}°C^{-1})	Specific heat (J kg^{-1}°C^{-1})		Emissivity
Material 1	25.8°C	3,090	14.38	156	0.9 [28]	
Working layer	238°C		7.31	600		
I	492°C		5.08	682		
Alumina-magnesia brick	744°C		4.23	713		
Alfrax F005	997°C		3.77	735		
(Saint-Gobain)	1,196°C		3.51	848		
Material 2	28°C	2,450	2.66	843	-	
Safety layer	238°C		2.19	1,117		
II	490°C		2.03	1,198		
High-alumina brick	742°C		2.03	1,261		
Mulfrax 1,400 C	994°C		1.93	1,400		
(Saint-Gobain)	1,244°C		1.43	2,249		
Material 3	200°C	570	0.26	965	-	
Foam insulator	500°C		0.28	1,060		
III	800°C		0.31	1,073		
Alumina insulating [24]	1,000°C		0.31	1,114		
	1,200°C		0.31	1,936		
Material 4	600°C	1,150 [19]	0.37 [19]	1,154 [19]	-	
Insulating castable	800°C		0.40 [19]	1,190 [19]		
III	1,000°C		0.40 [19]	1,215 [19]		
High-alumina castable	1,200°C		0.40 [19]	1,230 [19]		
Alfrax 90 VIC Saint-Gobain	1,400°C		0.46 [19]	-		
Material 5	400°C	510 [20]	0.25 [20]	1,047 [20]	-	
Fiber insulator	600°C		0.27 [20]			
III	800°C		0.31 [20]			
Alumina type SALI-2	1,200°C		0.38 [20]			
ZIRCAR Ceramics'	1,400°C		0.43 [20]			
	1,650°C		0.48 [20]			
Material 6 Shell	200°C	7,840 [21]	47.34 [22]	530	0.6 [23]	
IV	350°C		42.34 [22]	539[22]		
Low-carbon steel	500°C		37.35 [22]	667[22]		

collected from the technical datasheet.[19,20] Material 4 was evaluated by the steady-state heat flux technique and the thermal properties by means of the guarded-hot-plate apparatus (ASTM C177). On the other hand, Material 5 had its thermal conductivity measured by the calorimetry method (ASTM C201). The low-carbon steel thermal conductivity was based on the literature.[21–23] The specific heat for the different materials was obtained from other publications (see Table 1), simulated thermodynamically based on their composition (FactSage—6.4 version), or determined by the hot wire thermal diffusivity estimation, according to the equation:

$$\alpha = \frac{k}{\rho.c} \tag{1}$$

in which, $\alpha\alpha$is the thermal diffusivity ($m^2\ s^{-1}$), k is the thermal conductivity (W m^{-1} K^{-1}), $\rho$is the sample density (kg m^{-3}) e c is the specific heat (J kg^{-1} K^{-1}). The emissivity and density of all other materials were obtained in the literature, also shown in Table 1.

The three investigated thermal insulating materials present different properties and final application. They can be produced using different raw materials and methods, such as air or gas incorporation, adding low-density compounds, vacuum pressing, or a combination of techniques.[10,24,25] The use of ceramic fibers has some disadvantages, such as shrinkage and densification at high temperatures, higher prices and might be toxic to human beings.[26] Nevertheless, the insulator produced using small ceramic particles and gas incorporation enables

the manufacturing of ceramic foams with a high amount of evenly distributed small and closed pores, resulting in a material of lower and stable thermal conductivity at high temperatures (above 1,000°C).[26] The ceramic foam (Material 3), which was produced by this technique, also shows good dimensional stability and very low toxicity. It can also be manufactured with a customized microstructure for different applications, which is essential criteria to minimize the heat transfer, increase the mechanical resistance, and ensure a viable processing route.[1,10,25]

Thus, Material 3 was considered in all analyses where its thickness and lining position were changed. The other two insulators were investigated for comparative purposes: Material 4 is a high-alumina insulating castable, which presents high porosity and it is applied by vibration, and Material 5 consists of a combination of polycrystalline alumina fibers tightly bound into rigid plates, in a high-purity inorganic mullite binder matrix. The thermal conductivities of the insulating materials are compared in Figure 1. It can be observed that, among the three materials, the ceramic foam (Material 3) presents the lowest variation in the thermal conductivity with temperature (~16%) and the lowest values above 750°C. Conversely, the insulating castable presents an overall variation of 20% and the values increased with the temperature. The fiber insulating has a substantial increment in the thermal conductivity (48%) and the highest value at high temperatures. Those findings corroborate with what was previously mentioned about the better refractoriness of the ceramic foam.
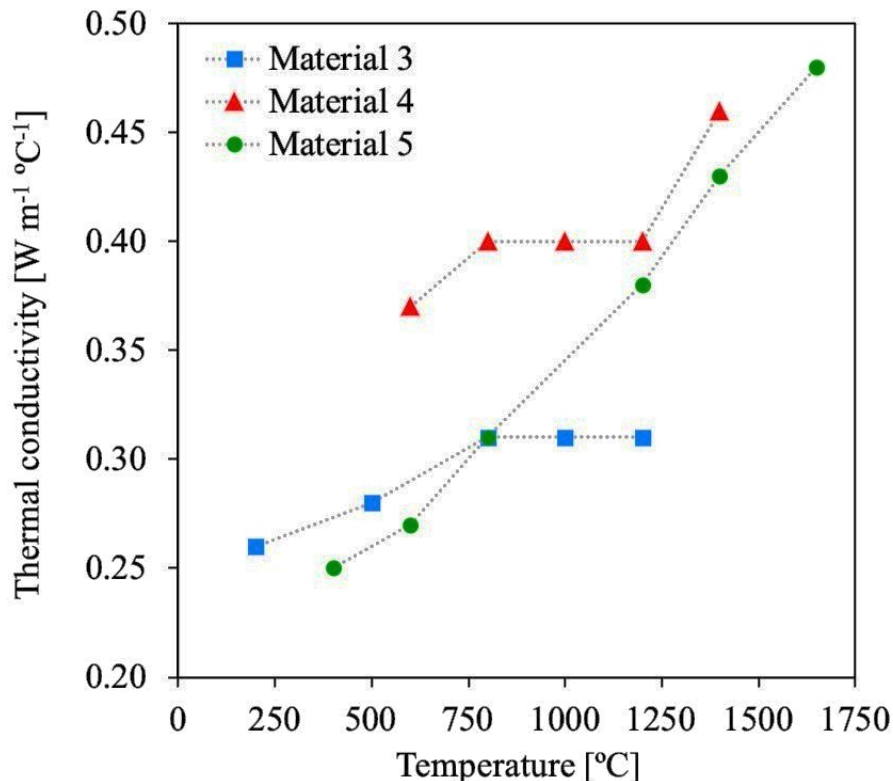

FIGURE 1 Thermal conductivity of different insulating materials (Material 3: foam; Material 4: castable; Material 5: fiber)

2.2 | Numerical model

In this study, the steel ladle cycle was simplified into four steps: heating, waiting (1 and 2) and holding. Figure 2 shows the time length of each step and how they were analyzed when comparing the different refractory lining configurations. The method is a general representation of the process, which enabled the investigation and comparison between the application of different types of insulating layers in the thermal performance of steel ladles. Herein, the heat transfer equation was solved numerically to determine all temperatures in the ladle domain according to refractory lining and property.

The ladle geometry and parts considered are represented in Figure 3. During the steel ladle pre-heating step, the new lining internal surfaces are heated up. The burner located in the central part of the heater lid produces a single flame that transfers heat mainly via radiation to the refractory, due to the high temperature of the combustion gases.[27] At the waiting steps, the ladle loses heat by convection and radiation mechanisms through all surfaces (internal and external). At the holding step, the heat transfer in the ladle internal surfaces is associated to the molten steel natural convection, the wall angle, and the longitudinal temperature variation of the refractory surface.

The thermal behavior of materials can be estimated by solving the heat transfer equation (Equation 2), leading to results related to the temperature profile, the heat flux, and the amount of energy transferred in the investigated systems. The presented model aims to solve an axisymmetric heat transfer problem for the temperature $T(r, z, t)$, by the equation below:

$$\rho c \dot{T} - div(k\nabla T) = 0 \tag{2}$$

where ρ is the material density (kg m^{-3}), c is the specific heat (J kg^{-1} °C^{-1}) and k is the thermal conductivity (W m^{-1}

°C^{-1}).[15] The equation boundary conditions are described in Table 2 for the convection and radiation mechanisms, according to each cycle step. The initial lining temperature and the room temperature was 40°C (T_{env}). The air temperature inside the ladle (T_{int}) was considered constant at 600°C. During the holding step, the molten steel initial temperature was 1,650°C (average tapping temperature).

Moreover, the average steel temperature drop during the analysis (dT_{steel}/dt) was calculated considering the energy lost to the refractories for each time increment, as shown in Equation (3).

$$\frac{dT_{steel}}{dt} = -\frac{1}{\rho_{steel}c_{steel}V} \int_{S_1 U S_2} q(r,z,t) \, dS \tag{3}$$

where ρ_{steel} is the molten steel density (7000 kg m^{-3}), c_{steel} is the specific heat (627 J kg^{-1} °C^{-1}), V the steel volume (m^3) and q (r, z, t) (J s^{-1} m^{-2}) the heat flux in the ladle internal surfaces. The average tapping temperature is subjected to a temperature drop associated to the refractory lining during holding, which results in the teeming temperature at the end of the holding step.

Finally, the energy evaluation was carried out by integrating the heat flux, with respect to the surface of interest and time (t), according to Santos et al.[17] Thus, the energy quantity, $E(t)$, is given by:

$$E(T) = \int_0^t \int_S q(r,z,t) \, dS \, dt \tag{4}$$

where S represents each surface (S1, S2, S3, S4) that transfers energy during the process. The energy losses at the top surface (border) are not considered in the energy balance.

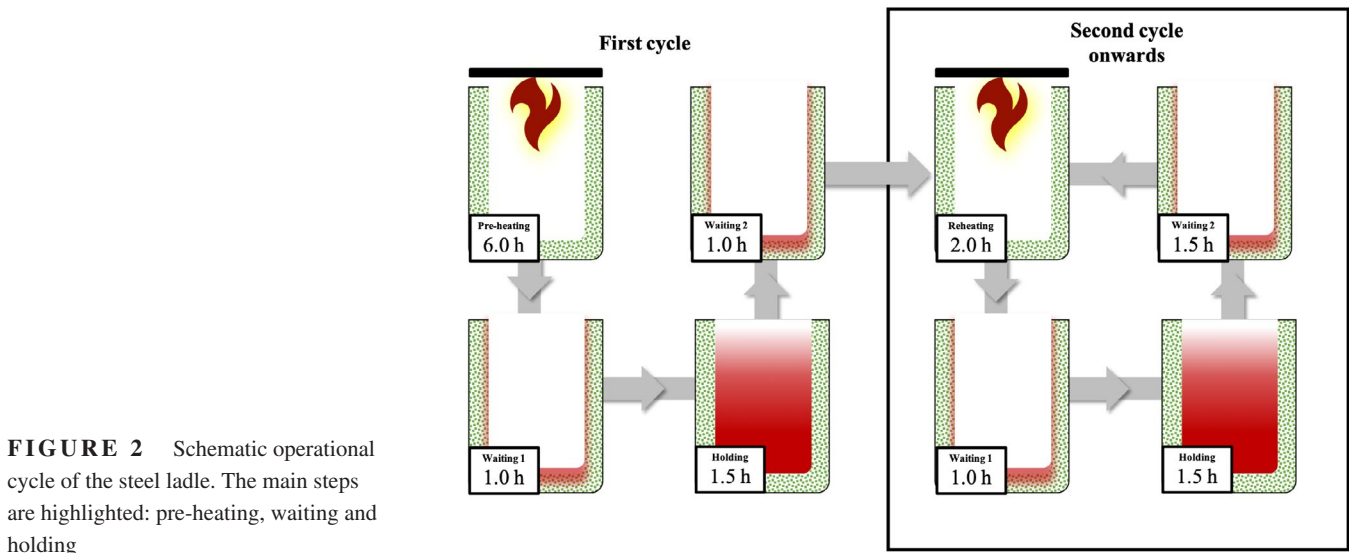**FIGURE 2** Schematic operational cycle of the steel ladle. The main steps are highlighted: pre-heating, waiting and holding
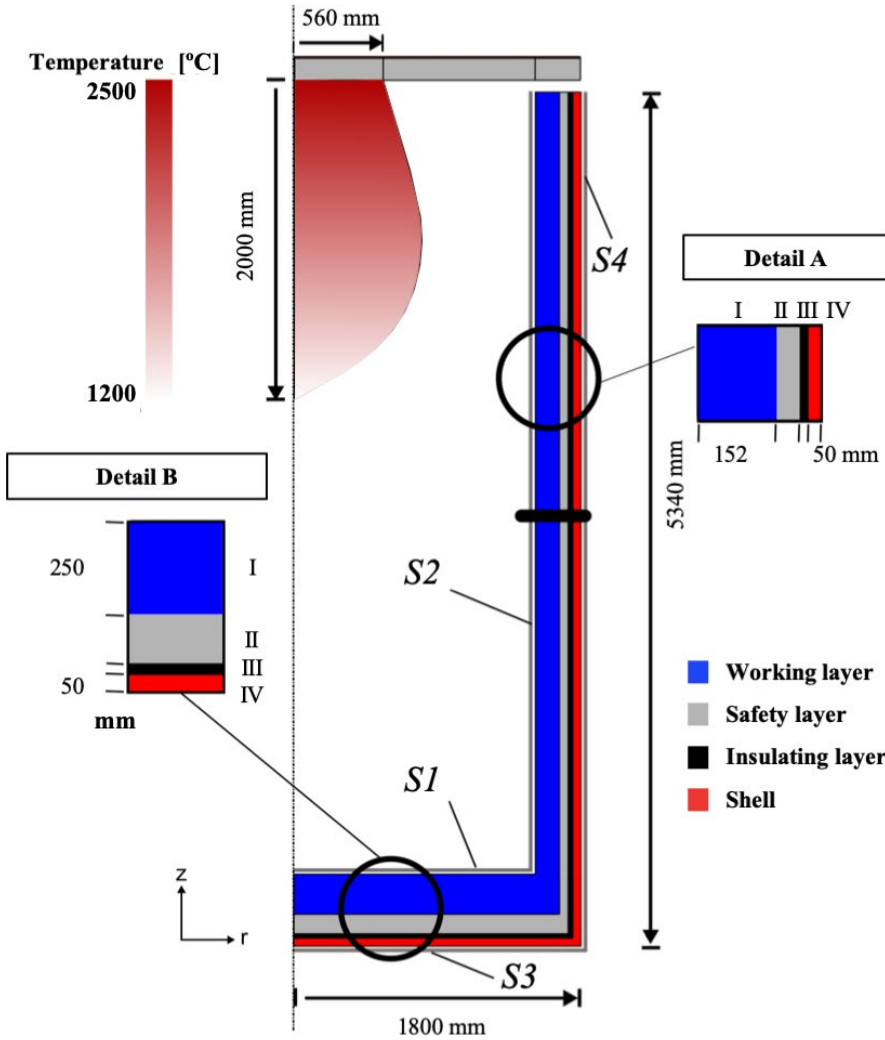
FIGURE 3 Geometry of the steel ladle and flame model. The details show the material locations considered for lining models

TABLE 2 Boundary conditions for each step of the ladle cycle

Process steps	Internal surface (S_1 and S_2)	External surface (S_3 and S_4)
Heating	$\sigma f \varepsilon_1 \left(T_{int}^4 - T^4 \right) + h_{air}(T) \left(T_{int} - T \right)$	$\sigma \varepsilon_2 f \left(T_{env}^4 - T^4 \right) + h_{air}(T) \left(T_{env} - T \right)$
Waiting 1 and Waiting 2	$\sigma f \varepsilon_1 \left(T_{int}^4 - T^4 \right) + h_{air}(T) \left(T_{int} - T \right)$	
Holding	$h_{steel}(T) \left(T_{steel} - T \right)$	

Note: N.B.: σ is the Stefan-Boltzmann coefficient ($\sigma = 5,6,697 \text{ Wm}^{-2}\text{K}^{-4}$); f the surface view factor; ε_1, the emissivity of the working layer; ε_1, the emissivity of the shell; T_{int}, the internal temperature of ladle; T_{env}, the external environment temperature; T_{steel}, the average steel temperature; h, the convection heat transfer coefficient ($\text{Wm}^{-2}\text{K}^{-1}$).

2.3 | Evaluated parameters

The investigation of the insulating layer on steel ladle linings aims to point out the influence of thickness, position and type of insulator on the average steel temperature drop at the end of the holding steps (energy consumption), the specific refractory consumption, the shell average temperature in different regions, the stored energy in the refractory lining, the average working layer temperature, and lastly, the hot face temperature change.

2.4 | Study cases

An axisymmetric ladle geometry (Figure 3) was considered to evaluate the influence of the thickness of the thermal insulating layer. This study investigated the performance of a new and a worn lining during the steel ladle cycle (see Figure 4 and Figure 5 for details of all configurations). The thickness of the insulating layer (Material 3) ranged from intervals of 7 mm to 14 mm, for the new and worn ladle, respectively. It started at 0 mm (configurations without the

insulating layer) to 84 mm (the whole safety layer is replaced by the thermal insulating material). Note that for the worn refractory lining, the thickness of the wall working layer was reduced by 84 mm (152 to 68 mm) and the bottom by 100 mm (250 to 150 mm), in order to represent the lining condition after approximately 60 cycles (average wear ratio of 1.9 mm per cycle).

The configurations of the insulating layer applied at the bottom are described for new and worn ladle lining conditions in Figure 5.

In addition, some particular configurations were also investigated, such as the application of a 21 mm insulating layer at the wall and at the bottom simultaneously; the effect of different types of insulators considering a 21 mm wall layer for a
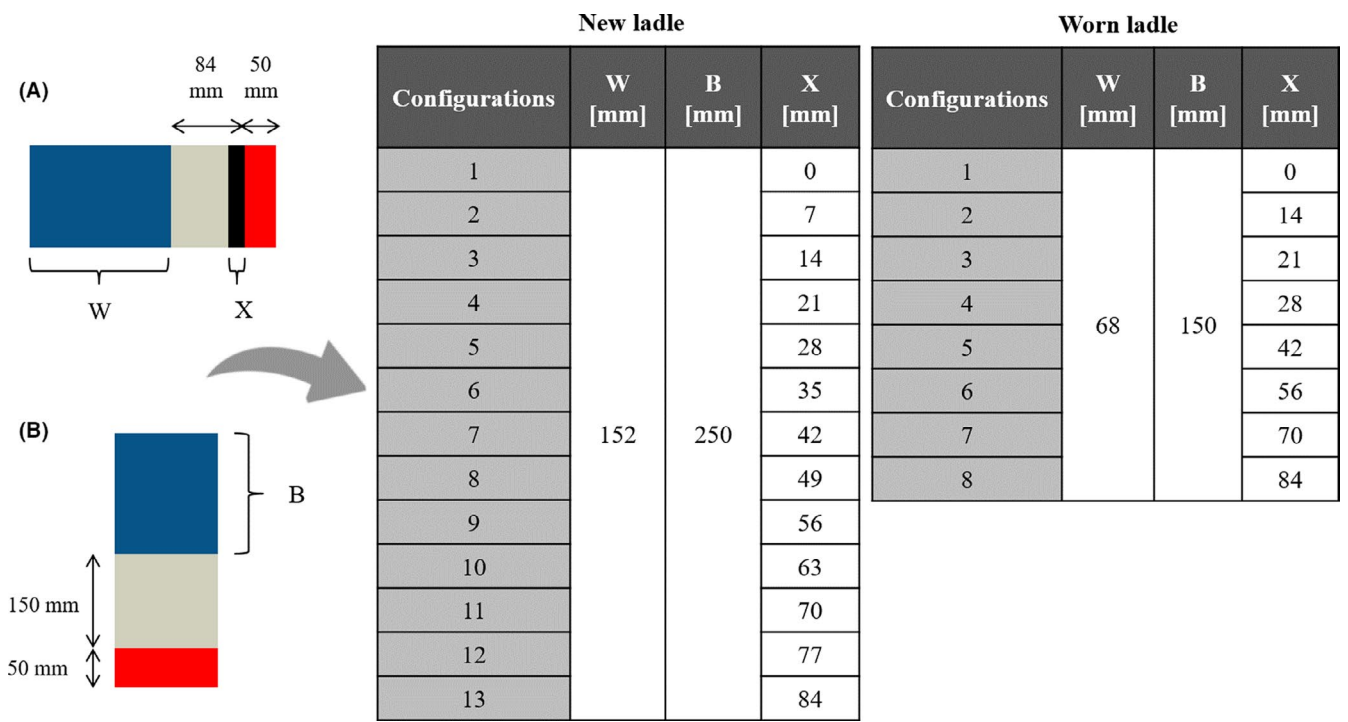

New ladle

Configurations	W [mm]	B [mm]	X [mm]
1			0
2			7
3			14
4			21
5			28
6			35
7	152	250	42
8			49
9			56
10			63
11			70
12			77
13			84

Worn ladle

Configurations	W [mm]	B [mm]	X [mm]
1			0
2			14
3			21
4	68	150	28
5			42
6			56
7			70
8			84

FIGURE 4 Configurations 1–13 are for the new ladle and 1–8 for the worn lining, considering the application of an insulating layer at the steel ladle wall. W represents the thickness of the wall working layer and B the bottom working layer. X is the insulator's thickness
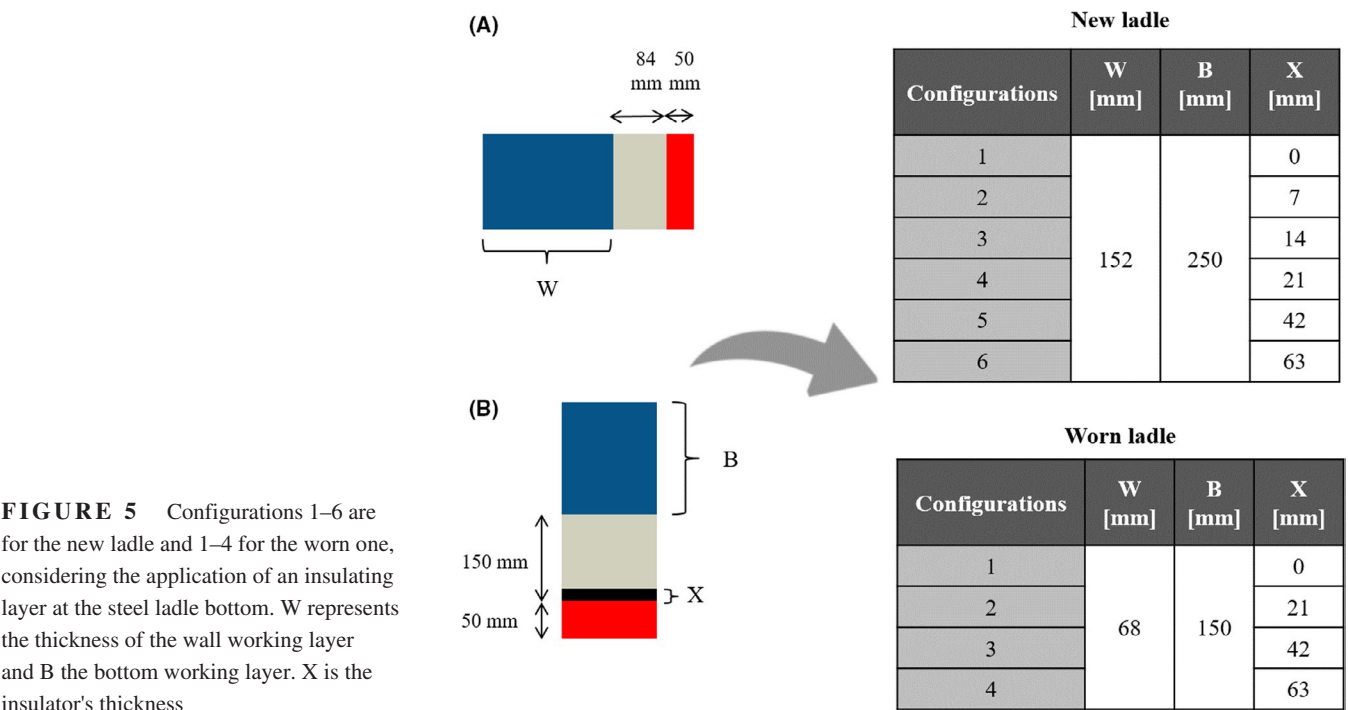

New ladle

Configurations	W [mm]	B [mm]	X [mm]
1			0
2			7
3			14
4	152	250	21
5			42
6			63

Worn ladle

Configurations	W [mm]	B [mm]	X [mm]
1			0
2			21
3	68	150	42
4			63

FIGURE 5 Configurations 1–6 are for the new ladle and 1–4 for the worn one, considering the application of an insulating layer at the steel ladle bottom. W represents the thickness of the wall working layer and B the bottom working layer. X is the insulator's thickness

new ladle; and non-usual positions of the insulator (between the safety and working layer and directly at the hot face).

3 | RESULTS AND DISCUSSIONS

The molten steel temperature is an important process parameter during the ladle cycle as it influences the bath internal reactions and the bath-refractory interactions. The molten steel temperature has a strong correlation with the quality of the steel products. For instance, the teeming temperature is directly related to the production flow and it can be associated to the molten steel temperature in the tundish (end of the ladle cycle). The results presented evaluated the average steel temperature during the holding step, which represents the secondary refinement temperature drop from tapping from the BOF converter to teeming, as briefly described in the modeling section.

Figure 6 shows the average molten steel temperature as a function of each investigated thickness of the insulating layer, considering the application of the foam insulator (Material 3). The temperature was analyzed for the last holding step after the sixth steel ladle cycle. In the plot, the green lines are related to the configurations in which the application of the insulating material is restricted to the wall and the blue ones only to the bottom region. A thicker insulating layer increases the average steel temperature, as the heat transfer between the bath and the lining is minimized. This is a consequence of the temperature difference between the bath and lining hot face, which is the driving force for convection, as shown in

Table 2. In the cases of greater insulation (larger thicknesses), the working layer temperature increases due to the stronger thermal barrier induced by the lower thermal conductivity material (foam insulator) that reduces the bath energy losses.

Placing the insulating layer only at the wall or bottom region showed the same behavior, although the effect on the average molten steel temperature is more significant for the wall cases (green lines in Figure 6). The impact is less significant at the bottom because the heat transfer is lower, the area is approximately 85% smaller, and the total thickness is 164 mm higher. The insulating layer effect on the wall showed a non-linear variation in the average molten steel temperature, and the increase in the thickness is more effective for small values. Because of that, the benefits of duplicating the foam insulator's thickness are reduced. To illustrate this, the 21-mm configuration raised the average steel temperature by 9°C, whereas the 42-mm one (double thickness) increased by 13°C (in respect to the configuration with no insulation), which is only 50% more efficient.

Figure 6 also shows the effect of the insulating layer on the average steel temperature considering the worn lining (solid lines). For this condition, the working layer has 68 mm at the wall and 150 mm at the bottom (all other conditions are maintained). The reduction on the total thickness results in lower heat capacity of the lining and higher heat losses during the waiting steps, mainly by the internal surfaces. The consequences are lower temperatures on the hot face and lining before tapping the molten steel from the BOF. This will lead to greater heat transfer from the molten steel to the lining, in order to compensate the higher losses in all surfaces
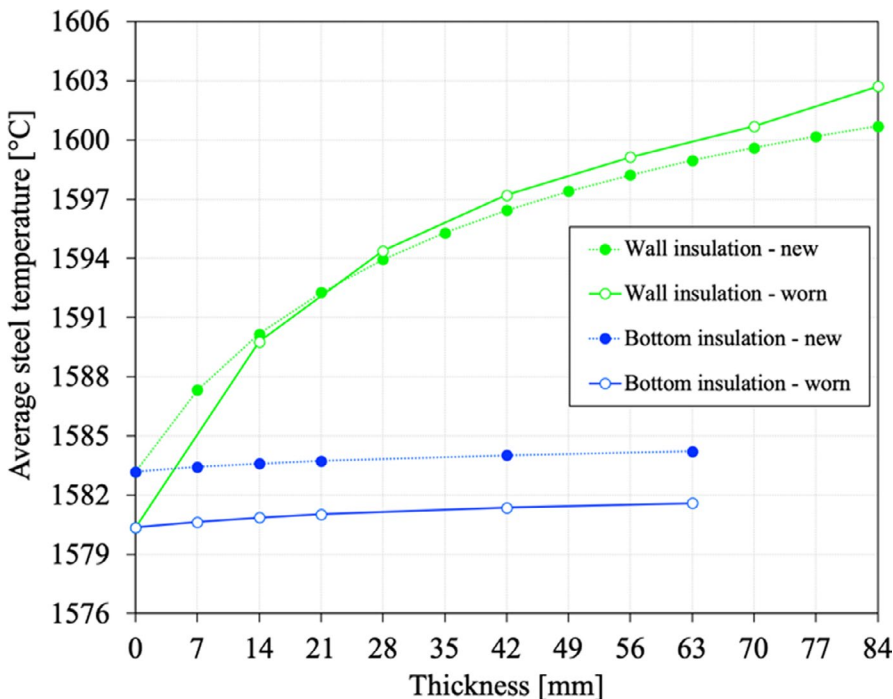

FIGURE 6 Average molten steel temperature for different insulator's thickness (Material 3) applied only at the bottom (blue lines) and only at the wall (green lines) for a new (dashed line) and worn (solid line) ladle lining

during the waiting step. However, it can also be seen that for a thicker wall insulator, the average steel temperature is higher for the worn configurations. The reason is that even though the heat losses increased, the ladle working capacity was incremented by 34 tons, affecting the amount of initial thermal energy in the bath (volume *V* in Equation 3). Hence, the differences in the average steel temperature throughout the ladle life are reduced for wall insulating thicknesses above 21 mm,

if assumed that larger amounts of steel are being processed. The worn configurations that had the foam insulator applied at the bottom also reduced the average steel temperature, but the results were not significantly influenced for the same reasons stated before.

As mentioned before, for the application of the foam insulator at the wall, the 21-mm configuration raised by 9°C the average steel temperature when compared to the one with
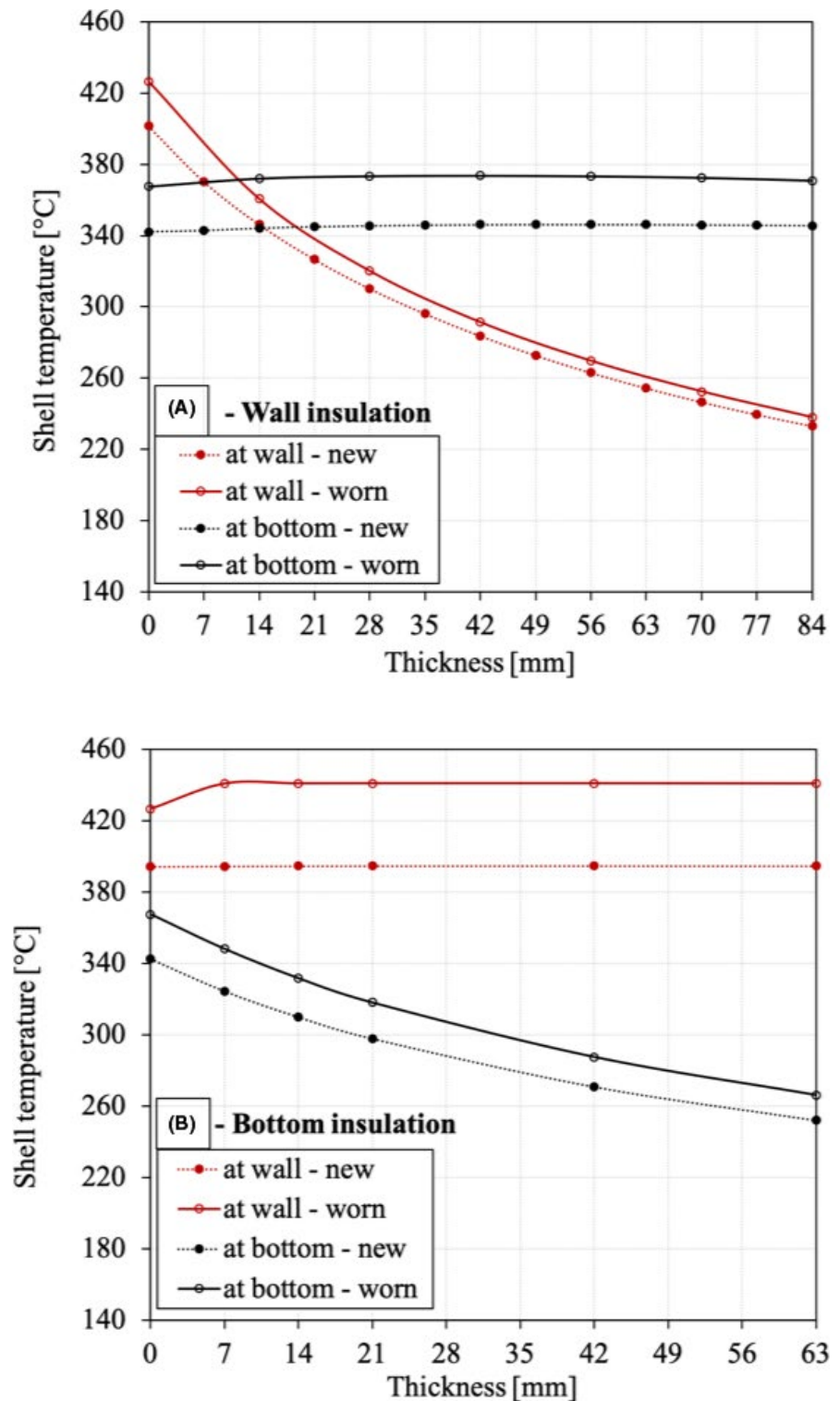
FIGURE 7 Shell temperature for different insulator's thickness (Material 3), where the red lines represent the wall and the black ones, the bottom. The dashed and solid lines are for the new and worn configurations, respectively. Plot A shows the effect of applying the insulation only at the wall and plot B exclusively at the bottom region

no insulation which represents approximately 50% of what is gained when using an 84-mm insulator. It also indicated smaller differences on the average steel temperature during the ladle cycle, which is certainly desired for better process control. Therefore, increasing the thickness of the insulating layer above 21 mm could incur higher costs and there is no guarantee of effectiveness throughout the production time.

The average shell temperature is presented for each configuration (new and worn lining) in Figure 7. Based on the geometry and process conditions of the studied ladle, the increase of the insulating layer thickness lowered the average shell temperatures. Approximately, each additional millimeter of insulating layer reduced by 2°C the average shell

temperature. Replacing the safety layer material (high-alumina) by a foam insulator (very low thermal conductivity) decreases the amount of transferred energy and consequently reduces the shell temperatures for the region where the insulator was applied. The region without this material shows that the shell temperature slightly increases due to the preferred heat transfer (Figure 7).

One of the proposed configurations considered the application of a 21 mm insulating layer on the wall and bottom linings simultaneously. In this case, the shell temperatures reduced in both regions, but the average steel temperature did not change significantly (1593°C for both regions to 1592°C for only at the wall). These results reinforce that adding an insulating layer at
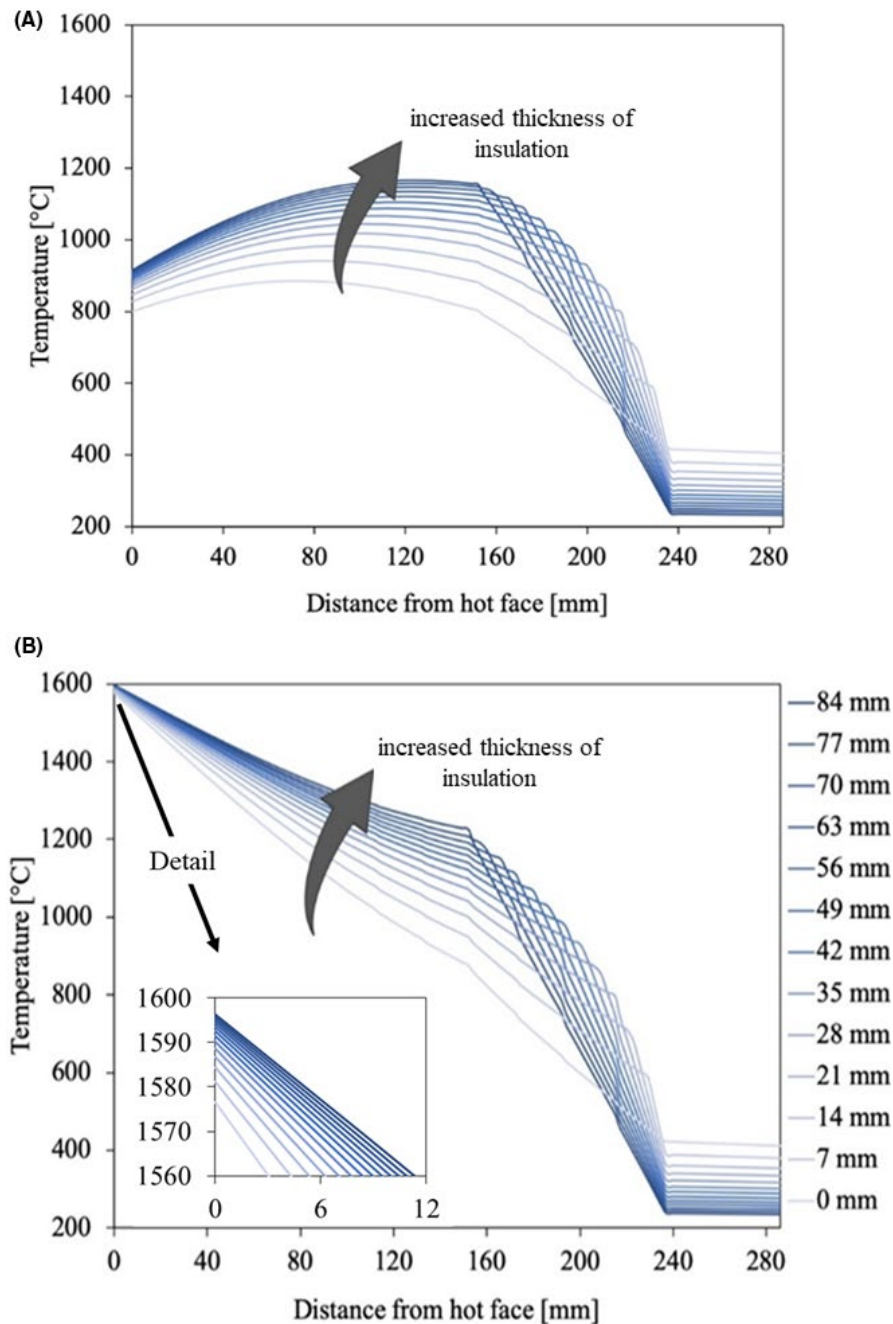

FIGURE 8 Temperature profile for different thickness of insulating layers (Material 3): (A) at the beginning and (B) the end of the holding step. The profiles were obtained for the wall at 2.5 meters height from the bottom lining. The arrow indicates the increase in the insulator lining thickness

the bottom affects only the average shell temperatures and it slightly influences the average steel temperature. Besides that, the higher ferrostatic pressure could reduce the bottom insulator performance due to compression effects.

Increasing the thickness of the insulating layer minimizes the total lining mass, as the density of the foam insulator is much lower than the high-alumina brick, even though they present similar chemical composition. It indicates that light materials in steelmaking installations could reduce the specific refractory consumption and the heat transfer while processing the molten metal. Additionally, the lower lining mass also reduces its capacity to store energy (thinner

high-alumina layer), as this energy will be preferably stored in the lining ahead of the insulating layer due to the thermal barrier imposed by the foam insulator.

Figure 8 highlights the temperature profile through the whole steel ladle wall, A) at the beginning of the holding step and B) after the holding step during the last cycle, for each investigated configuration (new lining). The results for the shell temperature correspond to what was stated before (Figure 7). Increasing the thickness of the foam insulator reduces the average shell temperatures. The comparison between the configuration with no insulation to the 84 mm one showed a temperature reduction of 179°C for the latter (and
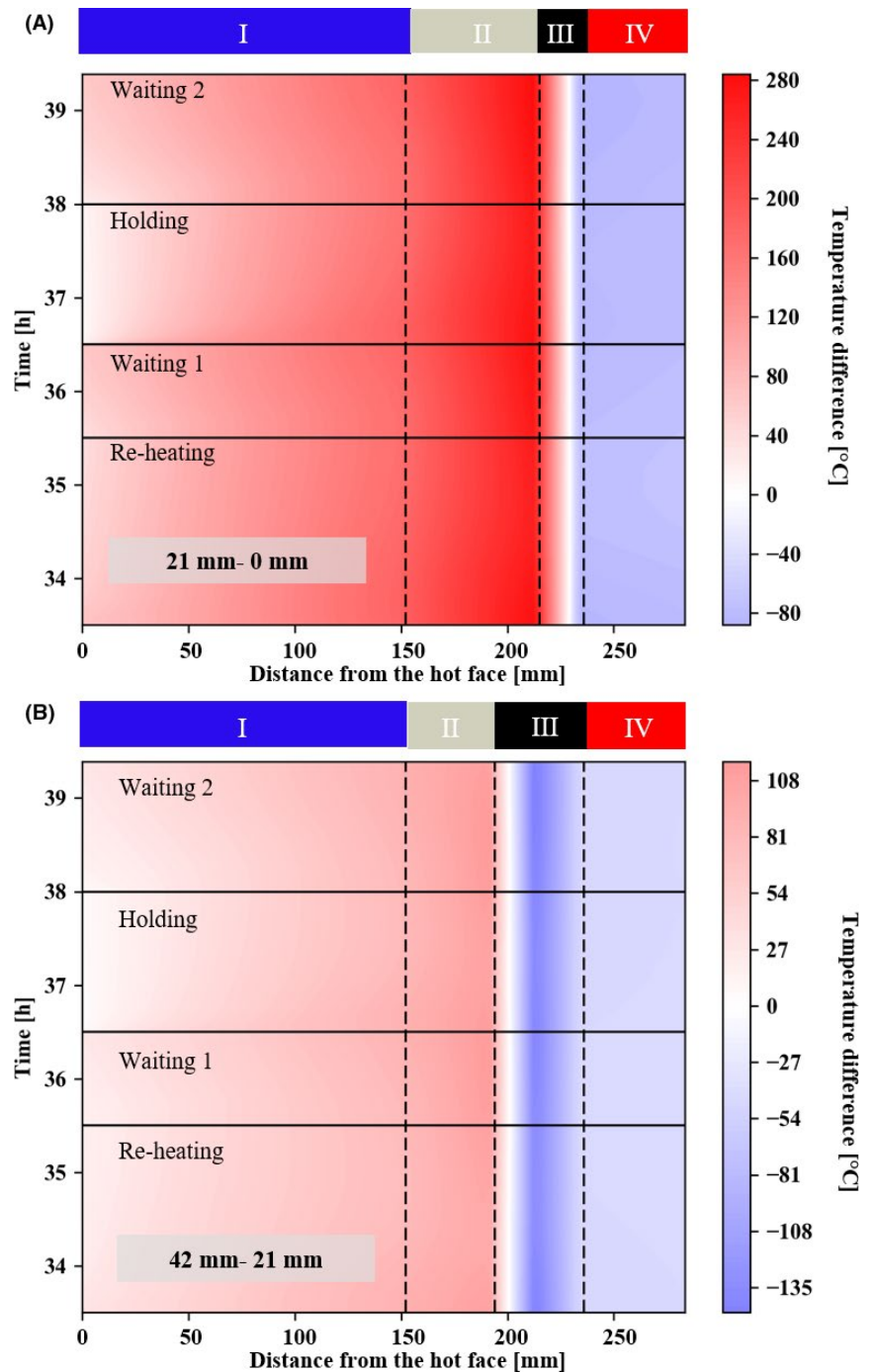

FIGURE 9 Temperature differences between the (A) 21 and 0 mm and (B) 42 and 21 mm insulating layer configurations. They were obtained for the wall at a height of 2.5 meters from the bottom lining

80°C reduction if compared to the 21 mm configuration). At the working and safety layer, the thicker insulation increased the temperature profile and the inner surface temperatures.

The average hot face temperature was 122°C higher for the configuration with 84 mm compared with the one without insulation, at the end of the waiting steps. On the other hand, at the end of the holding step, although the hot face temperature showed the same behavior as the waiting steps, the difference between the 84-mm configuration and the one with no insulation was reduced to 20°C. The lower working layer temperature gradient is an advantage, as it can decrease a likely thermal shock failure. Nevertheless, the average operating temperature of the refractory working layer becomes higher, which can result in higher creep and intensify the refractory corrosion closer to the hot face.

The temperature profiles for each time step in the last cycle were obtained for three insulator's thickness configurations: 0, 21, and 42 mm. By increasing the insulating layer thickness, the safety one was reduced, such as the same total lining dimension was maintained. In Figure 9, the temperature profile for each lining position is represented by the color gradient, highlighting the temperature difference between A) the 21 and 0 mm configuration and B) the 42 and 21 mm one. The red color indicates the position and time in which the 21 mm (Figure 9A) and 42 mm (Figure 9B) configurations resulted in higher temperatures and the blue color the regions in which they were lower. The white color represents none or a very small temperature difference between the analyzed configurations. Increasing the foam insulator's thickness from 0 to 21 mm and from 21 to 42 mm reduced the shell temperatures, on average by 80°C and 30°C, respectively, as shown by the bluish colors in Figure 9.

The results showed an opposite trend for the working and safety layers, as they presented higher temperatures than the configurations with lower insulation (reddish colors—approximately 280 and 100°C in Figure 9A,B, respectively). This also implies higher stored energy in the lining, mainly after the waiting step, which will decrease the heat losses when the ladle is filled in with molten steel. The stored energy density is expressed as the total thermal energy in the lining, normalized by the wall and safety layer mass, which are the regions that kept the energy absorbed from the molten steel. As previously mentioned, for the analysis, the safety layer is reduced to increase the insulating one, decreasing the available mass to store energy and forcing the energy to be concentrated closer to the hot face. The higher energy density in the working and safety layer is directly related to the energy loss from the molten steel during the holding stage, as shown in Figure 10. It reduces the energy transfer from the steel bath to the lining, keeping the average steel temperature higher (Figure 6). Besides that, the configurations ranging from 28 mm to 84 mm resulted in lower benefits per additional millimeter of foam insulator, which is an indicative that the working layer had been thermally soaked. This is also reflected on the non-linear behavior of the energy lost by the molten steel, seen in Figure 10.

The reduction in the molten steel energy loss when the foam insulator's thickness increases can be measured as a rate of energy losses per ton of steel produced (247 tons). The second column of Table 3 shows this data, where lower values indicate higher saving energy potential. The lower energy required to increase the average steel temperature during refining adjustments accounts as energy saving benefits. Alternatively, it suggests that lower tapping temperatures could be implemented in practice. Extra energy supply for the ladle process is associated with an exothermic reaction
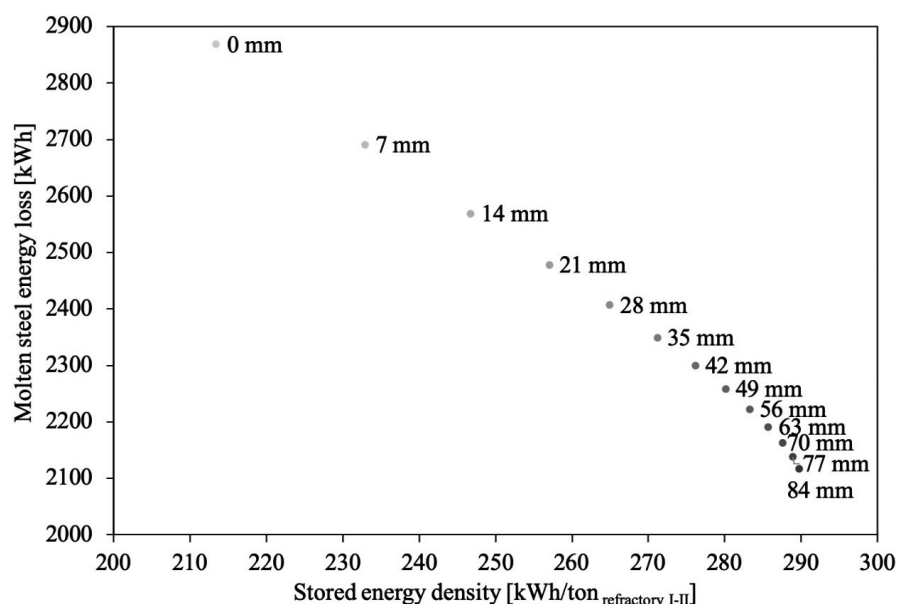

FIGURE 10 Stored energy normalized by the refractory mass (wall working and safety layers) before holding, plotted versus the molten steel energy loss during the holding step for different foam insulator thicknesses (Material 3)

TABLE 3 Comparison between the new and worn lining of steel ladle for different insulating layer thickness

Configurations		Energy loss during hold KWh/t	Molten steel temperature (°C)	Average shell temperature (°C)	Lining mass (ton)	Stored energy (KWh/ton refractory I-II)	Average temperature of the working layer (°C)	Average temperature of insulating layer (°C)	Variation of temperature in the hot face (°C)
New ladle									
0 mm		11.6	1583	402	71.7	213	1,172	-	777
7 mm		10.9	1587	370	70.9	219	1,216	512	753
14 mm		10.4	1,590	346	70.2	226	1,247	542	736
21 mm		10.1	1692	327	69.4	233	1,270	564	725
28 mm		9.8	1594	310	68.7	241	1,389	582	716
35 mm		9.5	1595	296	67.9	248	1,303	597	709
42 mm		9.3	1596	284	67.2	257	1,316	655	703
49 mm		9.2	1597	273	66.4	265	1,327	662	698
56 mm		9.0	1598	263	65.7	275	1,336	668	694
63 mm		8.9	1599	254	649	285	1,344	692	690
70 mm		8.8	1,600	247	64.2	295	1,351	714	687
77 mm		8.7	1,600	239	63.5	307	1,359	717	683
84 mm		9.6	1601	233	62.7	319	1,366	720	680
Worn ladle									
0 mm		12.1	1,580	426	56.8	254	1,371	-	835
14 mm		10.5	1,590	361	55.3	298	1,427	517	775
28 mm		9.7	1594	320	53.8	321	1,455	647	746
42 mm		9.2	1597	291	52.3	336	1,475	723	728
56 mm		8.9	1599	270	50.8	347	1,492	751	715
70 mm		8.6	1601	252	49.3	354	1513	808	712
84 mm		8.2	1603	238	47.8	357	1535	823	728

Note: ■ Working layer; ■ Safety layer; ■ Insulator; ■ shell

(aluminum addition) or electricity (ladle furnace—electrodes), depending on the steel mill. Table 3 also summarizes the results previously discussed, such as the average steel temperature, average shell temperature, lining weight, and stored energy density (before tapping) for each analysis´ configuration.

In Table 3, the effect of the insulator's thickness on the average temperature of the working layer (seventh column) is presented for the end of the holding step (values were obtained at the middle of this layer 2.5 m height from the bottom lining). The increase on the average refractory temperature can indicate a higher likelihood of thermal, chemical, and mechanical damage, considering the materials properties, the magnitude of the temperature and pressure on the hot face.

Increasing the insulating layer resulted in an increment of approximately 2°C on the average working layer temperature for each additional millimeter, which could be a disadvantage for the configurations with a thicker insulating layer. The same discussion is held for the average insulator temperature, as its thickness increase also affects its average temperature during operation. The last but one column in Table 3 highlights that the average temperature increases for thicker insulators, which could raise the damage likelihood (ie, creep) of the material, downgrading its efficiency as a thermal barrier.

Moreover, the temperature variation at the hot face of the lining between the end of the waiting step and the start of tapping (last column in Table 3 and Figure 8) was investigated. Increasing the thickness of the insulating layer minimizes
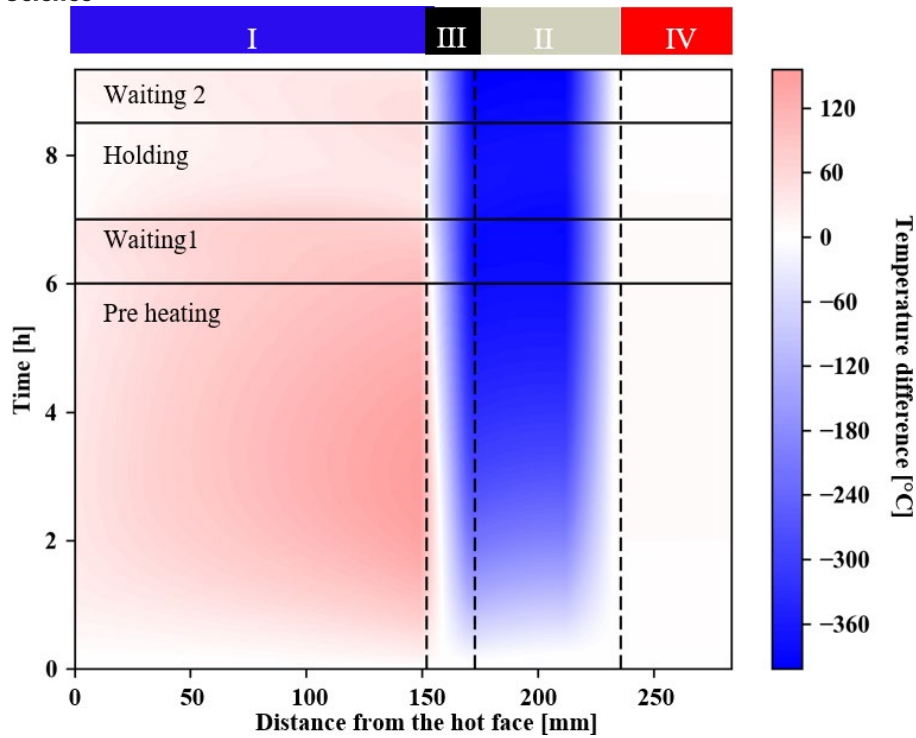
FIGURE 11 Temperature difference between the standard position and the one in which the insulating layer (III) is placed between the safety (II) and working layers (I), in the first cycle
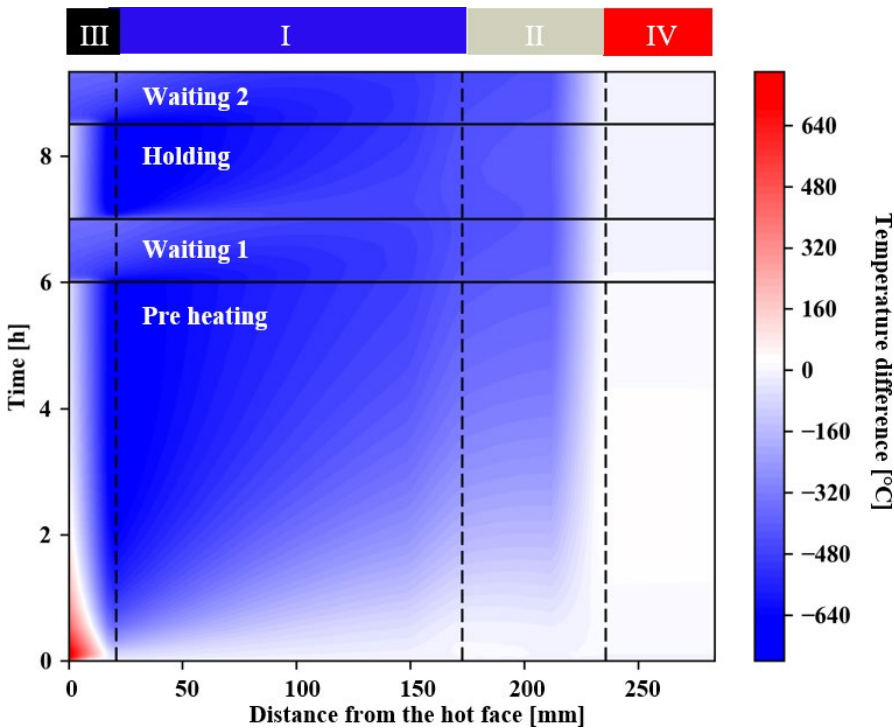

FIGURE 12 Temperature difference between the standard and hot face position for the insulating layer (III), in the first cycle

the temperature variation on the hot face (working layer). The molten steel is tapped into the ladle at 1,650°C on average and, if this condition is maintained, the configurations with thicker insulators would be subjected to a lower temperature variation at the hot face, reducing the probability of

damaging by thermal shock. Again, the benefits of reducing the temperature variation are more significant for thicknesses up to 28 mm.

Other scenarios were explored besides the usual position of the insulating layer (between the shell and safety layer).

FIGURE 13 Temperature profile considering the different types of insulators at the end of the holding step. Inset A shows the hot face and B the shell temperatures
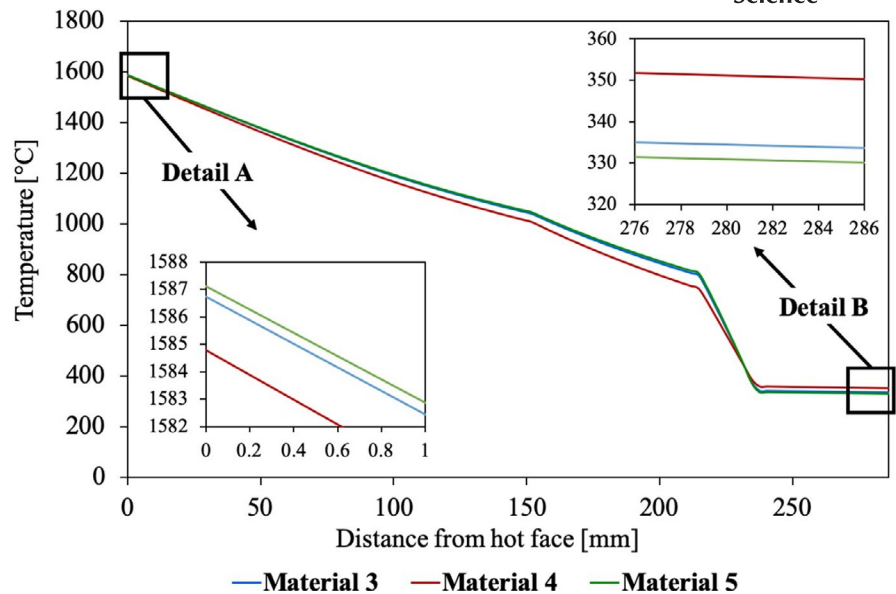
One analysis considered applying a 21 mm insulating layer at the wall between the working and safety layers, and the other directly at the hot face (as an "insulating coating"). The two scenarios considered the application of the foam insulator (Material 3), and they are less usual. However, they can point out optimized conditions or sometimes represent the reality of some steel mills or other metallurgical processes.

Based on such scenarios, Figure 11 shows that there are no significant temperature differences at the wall between the configurations with 21 mm at the usual position and the one between the working and safety layer. On the other hand, the safety layer (II) becomes significantly cooler as it is now positioned behind the insulating layer (III). Another advantage of this configuration is associated with the pre-heating step. Moving the thermal barrier closer to the hot face improves the heating of the working layer (reddish color in the pre-heating stage in Figure 11) because the energy used to heat up the safety layer is also absorbed by the working one.

If the 21 mm insulating layer configuration was positioned at the hot face, acting similar to a low thermal conductivity coating, the lining temperatures would significantly change, as shown in Figure 12. The working layer temperatures decrease by approximately 650°C, whereas the safety layer temperatures, around 300°C, and there are no considerable changes in the shell thermal condition. The application of porous materials in contact with molten metals is not a common practice in steel mills (even though it is more usual in foundries), because in general they would present low durability, low corrosion resistance and low mechanical integrity. However, studies in the literature have shown that microporous materials with low thermal conductivity could stand corrosive environments in contact with molten steel and slags, when properly designed to reduce the wettability

by those liquids [3]. Other studies highlighted strategies to also improve the mechanical resistance and thermal conductivity of insulators by correctly establishing the processing route and parameters [10,25]. Besides all restrictions, this scenario was evaluated only by thermal and energy aspects and it has shown that the average temperature of the molten steel after the holding step would be 1617°C, which means 34°C higher than the configuration with no insulation, and 25°C higher in comparison with the one with 21 mm at the usual position.

Lastly, different types of insulating materials (foam insulator, insulating castable, and fiber insulator) were investigated considering their regular placing position in the steel ladle practice. Figure 13 shows the temperature profile at the end of the holding step for each of the materials evaluated. The shell temperatures were lower for the fiber insulator (330°C), which is related to its lower thermal conductivity of Material 5 (see their differences in Figure 1) for temperatures below 750°C (this is the maximum average temperature of the insulating layer during the process on the default position. The foam insulator (Material 3) and the insulating castable (Material 4) increased by 4 and 20°C, respectively, the average shell temperatures when compared to Material 5. They do not show any considerable changes for the average molten steel temperatures: 1592, 1591, and 1593°C, for Materials 3, 4, and 5, respectively. For a full view of the potential results presented in this work, other aspects should also be considered, such as cost, durability, mechanical resistance, toxicity, dimension, stability, and installation process.

4 | CONCLUSIONS

Research on the application of insulating materials in steel ladle linings are of great importance, especially when

searching for thermal solutions in steelmaking. Despite the complexity, considering the high number of parameters that influence the thermal state of the ladle, it is fundamental to better understand the heat transfer in the process and to prospect novel and optimized lining designs, regarding the application of refractory and thermal insulator in the steel ladle lining.

Many steel industries do not use insulating materials for ladle linings, even though their application could result in a better performance. In this publication, the results stated the effectivity of these materials not only on reducing the shell temperatures, but also on increasing the average steel temperature that could account for energy savings. The gains of the insulator's thickness over 21 mm are less significant, pointing out that larger thicknesses could lead to higher costs.

The application of the insulator only at the wall is much more effective than applying it at the bottom. However, wherever the insulator layer is applied, the shell temperatures are significantly reduced. The insulating layer at the wall resulted in higher average steel temperatures than when at the bottom, whereas the shell temperatures still decreased at the bottom region when considering such configurations. In both cases, one could expect higher working temperatures of the refractory layers and lower temperature changes on the lining between the holding and waiting steps.

When considering the relative order of each layer regarding the standard position (ie, between the safety layer and the shell), the distinct types of insulating ceramics showed small differences on the ladle thermal profile. Nevertheless, the application of the foam insulator at less usual positions in the wall, between the safety and working layer and at the hot face, showed clearer effects. The first resulted in lower energy gains compared to the standard configuration but showed good performance during pre-heating. Conversely, the second changed the ladle thermal condition significantly and increased the molten steel temperature by approximately 34°C, which is a considerable energy saving scenario. The application of foam insulators in direct contact with molten steel and slag during the ladle refinement is a disruptive technique, but such technologies would be soon a reality, as they have been applied in other industries with a better performance.

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