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Influence on energy demand of thickness, thermal conductivity, and volumetric heat capacity of ladle working lining in secondary steel-making process

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Influence on energy demand of thickness, thermal conductivity, and volumetric heat capacity of ladle working lining in secondary steel-making process

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Abstract. The secondary steel-making process involves several steps during which steel is kept in a ladle, that is, a vessel made of an outer steel layer (carpentry), an intermediate refractory layer, and an internal refractory layer. Unlike the intermediate layer, the internal layer undergoes a progressive reduction in thickness and a periodic restoration. Traditionally, it is made of alumina or magnesite. During the process, the ladle undergoes unsteady heating and cooling; therefore, heat transfer depends on thermal conductivity and heat capacity. This study aims to identify the ladle internal layer characteristics that affect the energy demand. This analysis investigates the effect of the internal layer thickness *S*, volumetric heat capacity *C*, and thermal conductivity *λ*. Through the Design Of the Experiments (DOE), different scenarios have been selected and analyzed by means of numerical simulations performed on a numerical model defined in COMSOL Multiphysics. The energy demand as a function of the internal layer properties has been estimated, and it has emerged that low thermal conductivity and heat capacity values require a lower amount of energy.

Keywords: *Secondary steel making process, refractory materials, energy consumption, Design Of the Experiments, ladle.*

1. Introduction

1.1. The secondary steel-making process

The secondary steel-making process involves several steps during which steel is kept in a ladle as that schematized in figure 1. The ladle undergoes several production cycles which, according to figure 2, consist of several phases: preheating (only once at the beginning of a series of cycles), waiting while empty, filling with liquid steel poured from the electric arc furnace (EAF), heating using electrodes (LF), emptying in the continuous casting (CC), and cleaning. Along the process, the ladle undergoes heating and cooling which make the process unsteady and complex to be analyzed. During the steel-making process, several ladles are used in turns, and each of them undergoes between 70 and 90 cycles of use. In a standard cycle, before entering the production, gas burners placed inside the ladle preheat the internal surface to avoid thermal shocks and consequent breaks. If the wait between two cycles in a series is too long, the ladle is heated again, but this occurs rarely. After a certain period of waiting, the ladle is moved under the EAF furnace, where it is filled with steel and slag. Once filled, gas is continuously insufflated in the ladle to mix the steel and maintain its temperature as homogeneous as possible. Then, the ladle is sent to the LF station where ferroalloy is added to obtain the final composition, and energy (E_{LF}) is supplied using electrodes; since this is the last step where the steel temperature may be controlled, the energy supply must counteract energy losses due to heat transfer towards the ambient and the addition of materials at ambient temperature. Later, the ladle is closed with a lid to reduce energy losses and sent to the CC station where the steel is progressively drained and transformed into the final product. At this point, the ladle is sent to the cleaning station where slag and residuals of steel are removed. Finally, the ladle returns in front of the furnace to enter the next cycle.

In the literature, the secondary steel-making process was investigated from several points of view, with a particular interest in evaluating the heat transfer across the ladle surfaces [1-13]. Heat losses through the ladle were evaluated for the preheating phase with and without steel [3], for the tapping phase focusing on the effect of the slag characteristics (that is thickness, thermal properties, or by imposing a defined heat flux on the top surface) [4,5], and during the holding phase [6,7]. The study reported in [6] investigates the motion of particles in the liquid steel, and in [7] a simplified model for the heat loss from the molten steel to the refractory is proposed. Also, the thermal efficiency and mechanical strength of the ladle were analyzed [8,9]. The temperature distribution in the ladle was determined through a mathematical model in [10]. Other studies instead, analyzed the entire process, that is, from the tapping to the cleaning phases [11,12].

1.2. The ladle in the secondary steel-making process

Ladles are vessels made of an outer steel layer (carpentry), an intermediate refractory layer, and an internal refractory layer (figure 1). Unlike the intermediate layer, the working lining undergoes a progressive reduction in thickness and a periodic restoration. The intermediate layer is made of the so-called permanent lining, whereas the inner layer undergoes a progressive reduction in thickness and a periodic restoration: it is called either wear or working lining. Traditionally, the wear layer is made of alumina or magnesite, which differ in their thermophysical properties and manufacturing processes. The study presented in this paper analyses the energy demand E_{LF} in the secondary-steel-making process and, more precisely, how the characteristics of the working lining affect the energy demand in the LF facility. According to the study reported in [11], the energy demand in the LF depends on both thickness *S* and material used as working lining. However, the study was performed by considering real materials characterized by temperature-dependent properties, and this did not allow a full understanding of how single variables affect the energy demand. Given the complexity of the phenomenon, the numerical approach is the only viable method of investigation, since an experimental campaign would be prohibitively expensive, time-consuming, and influenced by production needs. Therefore, a simple but sound numerical model has been designed in COMSOL Multiphysics to simulate the process and focus on the working lining variables only. Experimental data have been used to validate the model as explained in [11]. The variables of the working lining have been analyzed using the Design Of the Experiments (DOE), a structured approach to collect data and to investigate the relationship between input and output variables [14].

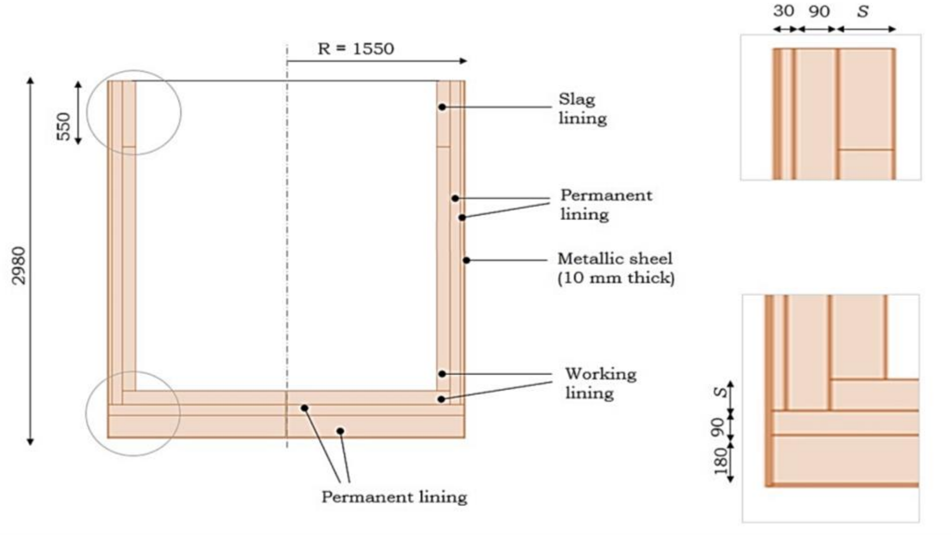

Figure 1. The geometry of the numerical model defined in COMSOL Multiphysics. Variations in the working lining properties and thickness *S* have been investigated. The dimensions are in millimeters.

2. Methods

The objective of this study is to provide manufacturers with suggestion on which material is the most efficient, that is, the materials that allow a greater energy savings. By means of numerical simulations, the effect of the working lining properties on the energy demand has been assessed. Several scenarios have been analyzed. They were identified through the Design Of the Experiments (DOE) technique, which allows to plan the tests to be performed. The DOE is generally used to plan experimental tests and it based on the principles of randomization, replication, and blocking

[15]; however, given that in this study data is obtained numerically, some assumptions could be neglected. Indeed, results obtained numerically are not affected by noise and sequence repetition.

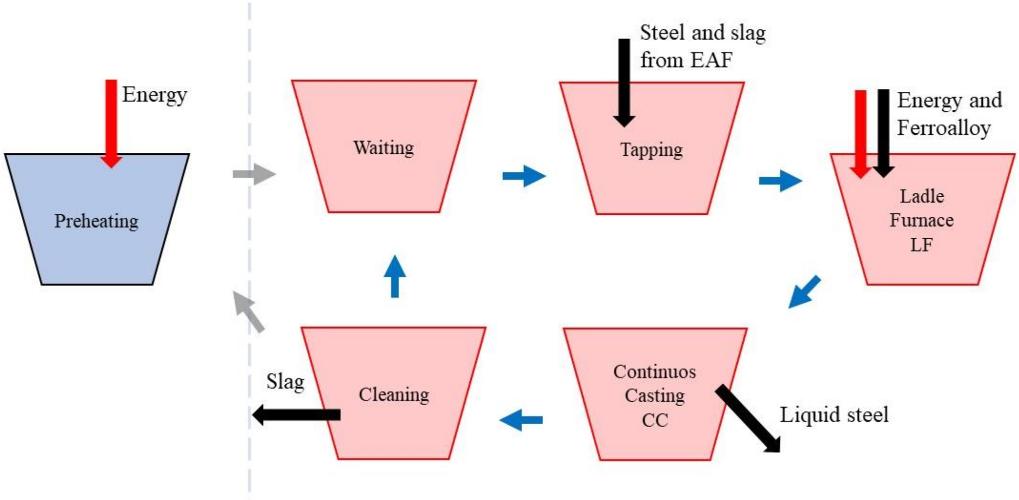

Figure 2. Phases that a ladle goes through in the secondary steelmaking process. After the cleaning phase, if necessary, the ladle can be resent to the preheating station.

2.1. Numerical model

Figure 1 shows the ladle geometry in which the working lining characteristics (thickness and thermal properties) varied while those of other layers remained constant. The process has been divided into cycles (*C*) and phases (*F*) as schematized in figure 3, and each phase has been modelled by means of one or more numerical simulations. To consider the variation of the liquid steel level along the process, the model geometry varied as shown in figure 3. The temperature detected at the end of each simulation has been set as initial conditions in the next one. The same initial volume of steel has been considered for the three thickness values considered, and this resulted in a higher steel free surface in the ladle with maximum thickness. The properties of the working lining have been identified as explained in section 2.2, while the properties of the other layers are reported in Table 1.

Table 1. Properties of the materials defined in the numerical model.

Material	ρ	c_p [kJ/(kg K)]	λ [W/(mK)]	ε [-]
Slag	2800 [13	0.52 [13]	0.48 [13]	0.6 [12]
Perm. lining (wall)	2700	1.05	2.3	-
Carpentry	7200 [13]	0.79 [13]	52 [13]	0.85
Perm. lining (bottom)	2100	1.05	2	-
Molten steel	6981	0.78	41	-
Lid internal	2390	1	1.35	0.45
Lid external	2390	1	1.35	0.52
Slag lining	3030	0.89 (200°C), 1.06 (700°C), 1.14 (1200°C)	8 (0°C), 6 (400°C), 4.8 (800°C), 4 (1200°C)	0.45

In the model, some simplifications have been adopted. The liquid steel convective motions in real ladles are forced by the insufflation of gas, but in the model the steel has been considered at uniform but time-dependent temperature by imposing an isothermal condition. Chemical composition effects have been neglected. On the ladle external surface, a mixed convective-radiative condition has been imposed (ambient temperature at 30 °C). The surface-to-surface radiation model is set on the internal surface of the ladle free from steel. Between steel and ladle, the perfect thermal contact condition has been imposed. Between the lid and the slag, the convective and radiative heat transfer is considered. The presence of the gas burners in the preheating phase *F1* has been modelled by imposing a temperature-time-dependent Dirichlet condition on the ladle's internal surface: the temperature *T* grows linearly from 30 °C to 1100 °C in 11 hours, while in the last 2 hours it is kept at 1100 °C. Then, the ladle waits ($F1_{bis}$) and in the filling phase (*F2*), it is full of steel and slag. In phase *F2*, the filling process has been considered instantaneous with an initial steel temperature of 1600 °C. Phase *F3* is representative of the process in the *LF* where energy E_{LF} is supplied to the steel. In real processes, E_{LF} varies depending on many variables. In our model it has been calculated in the following way.

Time duration of phase *F3* is fixed and equal to $\Delta T = 2400$ s (40 minutes). During phase F3 a uniform and constant volumetric source term q''' is imposed to the steel. Through an iterative process, the value of q''' is determined as the value that allows the steel to reach the threshold temperature of 1595 °C in $\Delta T = 2400$ s. The energy supplied is computed as $E_{LF} = q'''\cdot V\cdot \Delta t$, where V is the steel volume. In phase *F4*, the ladle is closed with a lid which is at an initial temperature of 250 °C. The emptying in the continuous casting CC (phase *F5*) has been analyzed through 11 numerical simulations in which the steel level has been progressively lowered by 200 mm from one simulation to the next one. The ladle in phases *F6* and *F7* is empty, and convection and radiation are set on all surfaces. To approach the steady condition, the simulation process has been repeated for several cycles. Therefore, for each case, 100 numerical simulations have been performed to simulate the steel making process in the first seven cycles: indeed, the first cycle *C1* counts eight phases (*F1-F7*) because of the preheating *F1* and waiting $F1_{bis}$ phases, while the following ones, *C2-C6,* only six phases (*F2-F7*).

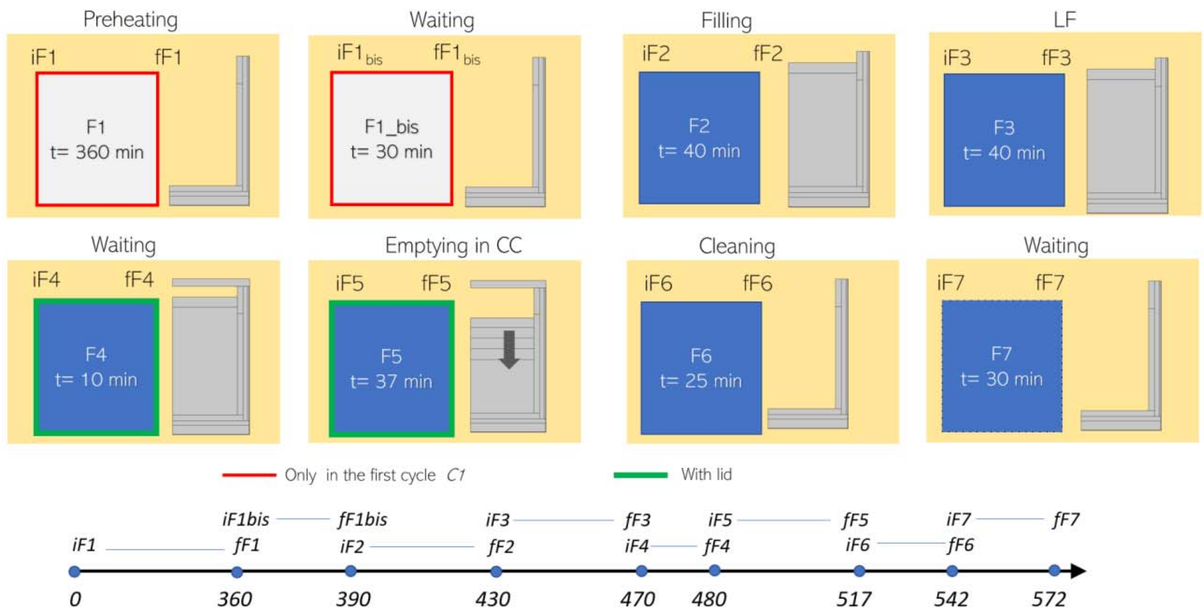

Figure 3. Representation of the phases in a cycle with their time duration. Phase *F5* has been divided into 11 sub-phases in which the level of the steel is progressively lowered. Phases *F1* and $F1_{bis}$ are present in the first cycle only, while the lid is present only in phases *F4* and *F5*.

2.2. *Design Of the Experiments: selection of levels and factors*

The Design Of the Experiments (DOE) is a technique used to systematically classify and quantify cause-and-effect relations between variables and outputs [14]. To apply this technique, it is necessary to identify the study objective, the variables affecting the phenomenon under analysis called *factors*, the range of the variables called *levels*, the experimental design type (fractional or full factorial design), and the type of experiments (experimental or numerical experiments). The objective of the study is to assess if and how the characteristics/properties of the working lining affect the energy demand in the secondary steel making process. In [11], it emerged that heat transfer through the ladle surface is influenced by thickness and working lining material. However, since real materials were considered and, therefore, temperature-dependent thermal properties, it is not understandable how density ρ, thermal conductivity λ, and specific heat c affect the energy demand. This type of analysis is performed in this paper, where each variable is analyzed separately. Through the Design Of the Experiments (DOE) technique, different scenarios have been identified. As can be seen in figure 4, three factors have been considered, that are, thickness S, thermal conductivity λ, and volumetric heat capacity C (obtained as the product of density ρ and specific heat c). Based on surveys of refractory material producers (who wish to remain anonymous), the range of each variable has been determined. Due to the possibility that the response to a factor variation may not be linear, three levels have been determined that can detect the possibility of a curvature in the response. The properties have been considered constant, and the identified levels for the thickness S are 80, 115 and 150 mm, for the thermal conductivity λ are 1, 5.5, and 10 W/mK, for the specific heat c are 800, 1150, and 1500 J/kg K, for the density ρ are 2000, 2750, and 3500 kg/m^3. Therefore, three levels and three factors have been considered, with a total of 3^3 cases to be analysed (figure 4). The intermediate value of the volumetric heat capacity C is the product of the intermediate level of ρ and c, with consequent values that are not the central one. By comparing the estimated energy-demand E_{LF} for each analyzed case, it has been possible to assess the influence of each factor as better explained in the following section. Referring to table 2, by comparing the results obtained for *Mat 1_1*, *Mat 2_1*, *Mat 3_1* the influence of the volumetric heat capacity is assessed. By comparing the results obtained for *Mat 1_1*, *Mat 1_2*, *Mat 1_3* the influence of the thermal conductivity is assessed. The initial idea was to test all the combinations but, successively, it has been decided to test only one scenario for the intermediate and the minimum thicknesses.

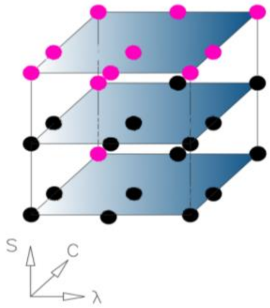

Figure 4. Representation of the factorial design considered in the study. Numerical experiments have been performed for the scenarios in red color only.

Table 2. Levels identified for the thermal conductivity λ and the volumetric heat capacity *C*. Materials resulting from this process are fictitious since they are not representative of real materials. In the nomenclature, the first number refers to the volumetric heat capacity.

		Low	Int	High
	C [kJ/kg m^3] / **λ [W/mK]**	**1600**	**3162.5**	**5250**
Low	**1**	Mat 1_1	Mat 2_1	Mat 3_1
Int	**5.5**	Mat 1_2	Mat 2_2	Mat 3_2
High	**10**	Mat 1_3	Mat 2_3	Mat 3_3

3. Results and discussion

Results of the numerical analysis reported in figures 5-10 are discussed to assess the influence of the working lining thermal conductivity *λ*, volumetric heat capacity *C*, and thickness *S*. According to figures 5 and 6, there is a greater difference between the energy demand in successive cycles at the beginning of the process, specifically between cycles *C1* and *C2*. In phase *F1*, present only in cycle *C1*, the ladle is heated with gas burners, and the temperature on the internal surface at the end of the process is 1100°C. Depending on the ladle characteristics, the temperature of the liquid steel varies between 1600°C and 1300°C throughout the cycle. Steel's initial temperature is higher than the temperature imposed at the end of preheating phase, so the ladle heats up when it comes in contact with it. In phase *F3* of the first cycle *C1*, the ladle has been in contact with liquid steel for 40 minutes only and, therefore, a higher quantity of energy is required to reach the threshold steel temperature. In the following cycles (*C2-C7*), less energy is required thanks to the longer contact with the liquid steel. In figure 5, at the beginning of the process, in cycle *C1,* the energy demand is lower for the minimum thickness but, after four cycles, the highest energy demand is related to the intermediate thickness (S_{int}). In the seventh cycle, the highest energy demand is estimated for the minimum (S_{min}) and intermediate (S_{int}) thicknesses. To better understand the causes of these differences, the temperature detected along the ladle wall for different thickness values (but same volumetric heat capacity and thermal conductivity) at the end of the preheating phase (*F1*) are reported in figure 7. The difference in energy demand is due to the opposite effect played by the working lining thickness: a greater thickness offers a greater thermal resistance but, at the same time, a greater heat capacity. On the other hand, the scenario with the greater thickness has a limited heat exchange surface. Figure 6 shows the energy demand E_{LF} required along the process as a function of the working lining thermal conductivity and of the volumetric heat capacity. The energy demand shows higher values at the beginning of the process, and the steady condition is approached depending on the scenario. A dependency on the material properties is also detected at the beginning of the process. Thermal conductivity *λ* strongly affects the energy demand since, for *C* equal to 5250 kJ/kg m^3, it ranges between 1 MWh (for λ=1 W/mK, *Mat 3_1*) and 2.4 MWh (for λ=10 W/mK, *Mat 3_3*). As regards the effect of the volumetric heat capacity, for *λ* equal to 10 W/mK, E_{LF} ranges between 1.7 MW (for C=1600 kJ/m^3 K, *Mat 1_3*) and 2.4 MW (for *C*=5250 kJ/m^3 K, *Mat 3_3*). Therefore, a correlation between the thermal conductivity and the volumetric heat capacity is detected but not

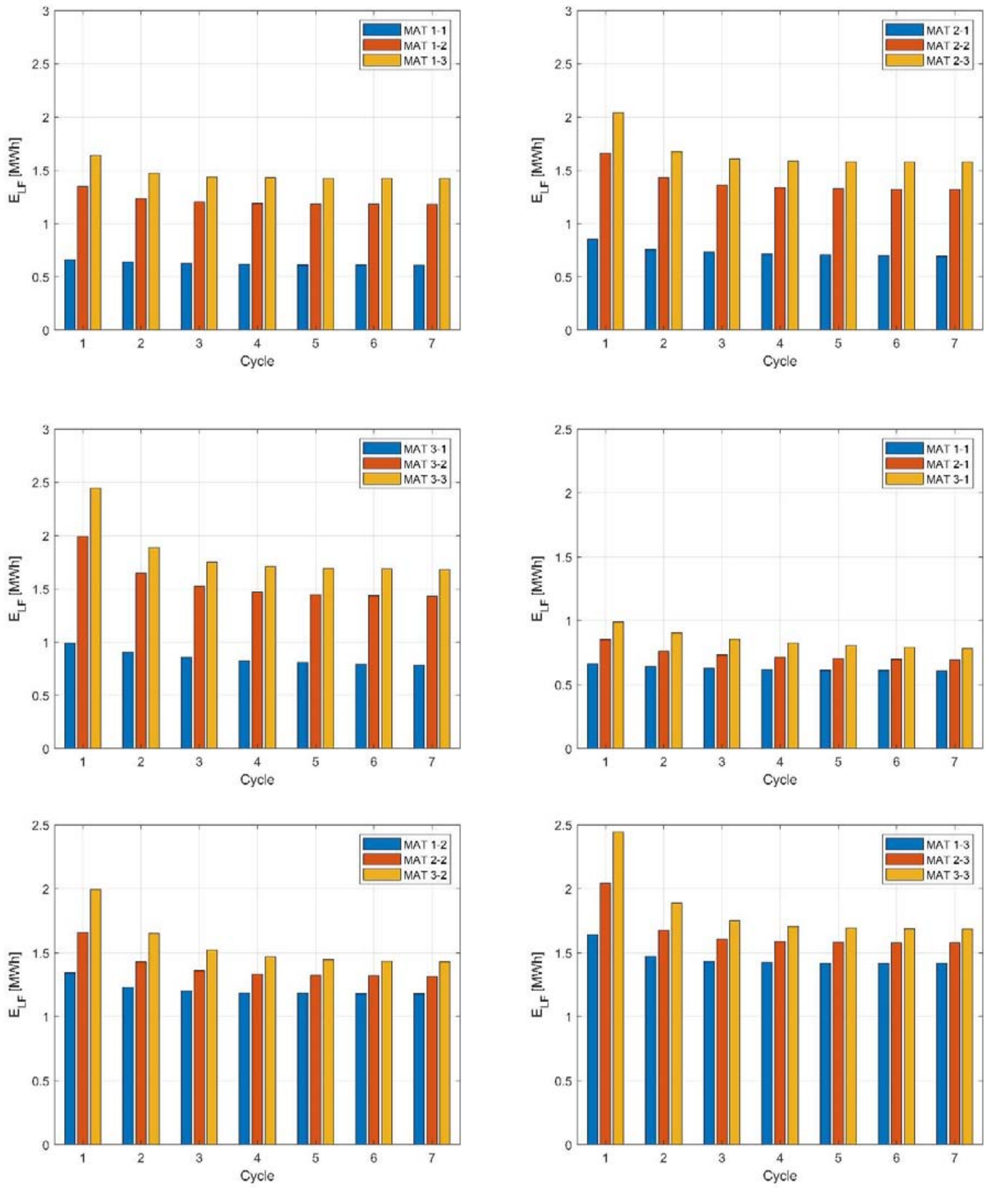

Figure 5. Energy demand E_{LF} as a function of the cycle for different scenarios. The first subscript in the scenario name refers to the volumetric heat capacity *C*, while the second one to the thermal conductivity *λ*.

quantified. Figure 8 shows the temperature distribution along the ladle wall at the end of the preheating phase, where it is confirmed that thermal conductivity influences the initial condition strongly. The E_{LF} values estimated for *C7* are shown in figure 9 for varying *C* and *λ*. The trend for the highest conductivity values is non-linear as a function of volumetric heat capacity. On the other hand, the energy trend depends strongly on thermal conductivity. In contrast, the variation as a function of thickness is limited and lower than 0.1 MWh (0.78 MWh for S=150 mm, 0.80 MWh for

S=115 mm, 0.80 MWh for S=80 mm), as also observed in [11]. Therefore, this factor can be neglected in the analysis to limit the number of experiments to be conducted.

4. Conclusions

The study analyzed the energy consumption in the secondary steelmaking process as a function of working lining characteristics. The study has been performed through numerical simulations performed with COMSOL Multiphysics and the analyzed scenarios have been selected through the DOE technique. Three factors and three levels have been identified for a total of 27 cases, of which only 11 have been analyzed. The identified factors are the working lining thickness, volumetric heat capacity, and thermal conductivity. A total of 1000 numerical simulations have been performed to determine the energy demand supplied in the electric arc furnace to guarantee a threshold temperature of the liquid steel. The results show that the most influencing factor is the thermal conductivity, with lower energy consumption for the material with the lower conductivity value. Heat capacity also affects energy consumption with lower values for lower values of heat capacity. Finally, thickness does not heavily affect the results, indicating that the heat transfer phenomenon can be treated by leaving out this variable, which makes the analysis much simpler.

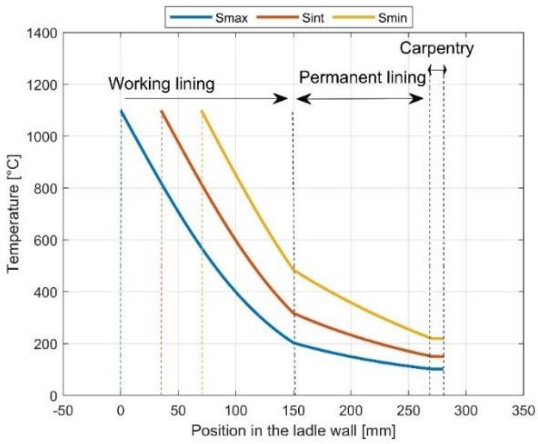

Figure 6. Temperature distribution in the ladle wall as a function of the working lining thickness *S*, at the end of the preheating phase *F1*.

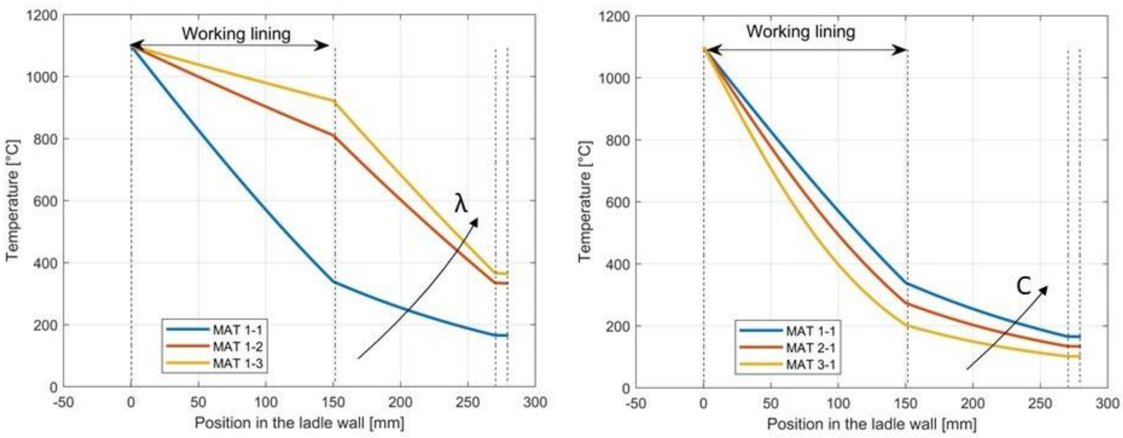

Figure 7. Temperature distribution along the ladle wall at the end of the preheating phase *F1* in the first cycle *C1* as a function of the thermal conductivity λ, and of the volumetric heat capacity *C*.

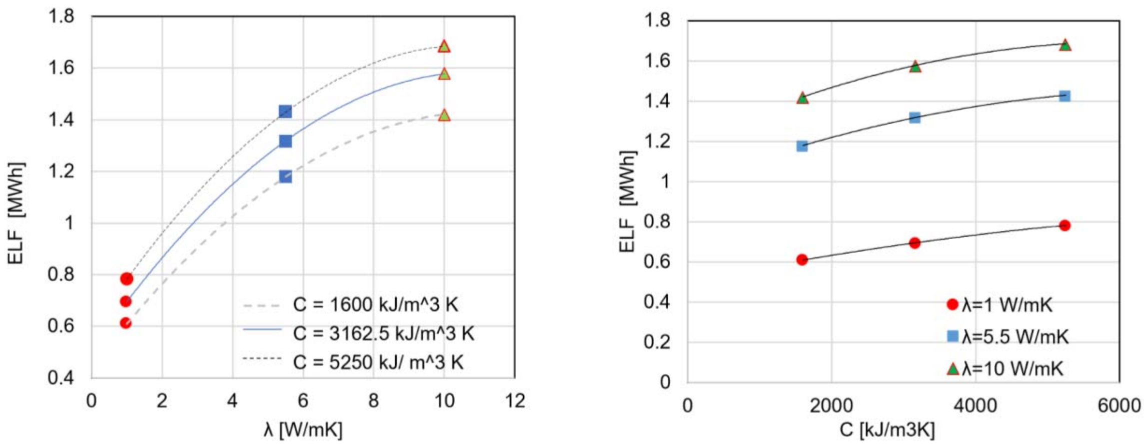

Figure 8. Energy demand E_{LF} as a function of the thermal conductivity λ and of the heat capacity *C*, estimated for S_{max} at the end of the process (cycle *C7)*.

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