encit 2020

ABCM
Associação Brasileira de Engenharia e Ciências Mecânicas

18th Brazilian Congress of Thermal Sciences and Engineering
November 16-20, 2020 (Online)

ENC-2020-0015
REHEATING FURNACES IN THE STEEL INDUSTRY: REDUCTION OF HEAT TRANSFER LOSSES BY ANALYZING THE TYPES OF INSULATION MATERIALS AND THICKNESS IN EACH LAYER

Diego Jhovanny Mariños Rosado
Samir Boset Rojas Chávez
Jordan Amaro Gutierrez
João Andrade de Carvalho Jr
São Paulo State University, Mechanical Engineering Faculty, Av. Ariberto P. Cunha, 333, Guaratinguetá, SP, CEP 12510-410, Brazil
diego.marinos@unesp.br; samir.rojaschavez@hotmail.com; jordan.amaro.gutierrez7@gmail.com; ja.carvalho@unesp.br

Miguel Angel Huaraz Rodriguez
National University of Santa, Energy and Physics Department, Av. Pacífico 508. Chimbote, Ancash, Peru.
huarazmiguel.r@gmail.com

Andrés Armando Mendiburu Zevallos
Rio Grande Do Sul Federal University, Mechanical Engineering Department, Av. Paulo, 110, Porto Alegre, RS, CEP 90040-060, Brazil
andresmendiburu@ufrgs.br

Abstract. *The purpose of applying heat transfer in the reheating furnace was to quantify the heat lost through the roof, walls and floor of the furnace, as well as to quantify the temperatures in each layer. To evaluate the heat rate, coatings of different materials with a thickness in each layer and different configurations between them were used. In the case of the roof it was evaluated with 3 types of materials, in the case of the walls and floor 18 and 5 configurations were made, respectively. It is evident that the losses due to the heat transfer in the furnace were reduced below 2%, analyzing the setting that presented the lowest heat rate. On the roof, the temperature in the last layer was 72.9 °C; on the wall, the temperature in the outer layer was 88.2 °C; and on the floor, the temperature in the outer layer was 73.6 °C. Finally, the heat rate obtained in the roof, wall and floor of the furnace was 952.11 W/m^2, 813.45 W/m^2, and 606.80 W/m^2, respectively.*

Keywords: *heat rate, heat transfer losses, insulation materials, reheating furnaces, steel industry.*

1. INTRODUCTION

Reheating furnaces are widely used in industry, both nationally and globally, and constitute the second largest consumers of energy and producers of CO_2 (Trinks *et al.*, 2004). Like the refrigeration industry, they are large consumers of energy. In the steel industry, control strategies must be established that lead them to a framework of competitiveness and efficient production (Mariños *et al.*, 2019).

These furnaces are used to raise the temperature of the steel passing through them, from room temperature to a temperature of around 1280 K or even higher in some cases, in order to undergo subsequent formation and thermal treatment. Walking-beam type reheating furnaces are those in which the billets move along the furnace by means of a reciprocating movement mechanism. The performance of these furnaces can have a significant impact on the quality and total cost of the final product (Trinks *et al.*, 2004).

Venturino and Rubini (1995) carried out the first numerical study of a walking-beam type reheating furnace while considering the combustion process, presenting a methodology similar to the one used by Li *et al*. (1988). In this methodology, the heat transfer inside the furnace and the heating of the slabs are modeled in two separate simulations. The results of the heat fluxes in the first simulation are used as boundary conditions to calculate the heating of the slabs. Unlike the Li et al. method, which only takes into account the radiation and the temperature of the walls and assumes fixed gases from experimental measurements, Venturino and Rubini's case models the heat transfer in the furnace using CFD, taking combustion into account. As the temperature of the slabs is a factor that alters the results of the calculation of heat transfer in the furnace, Venturino and Rubini propose an iterative methodology for calculating both the heat transfer in the furnace and the heating of the slabs.

Another method is proposed by Zhang *et al.* (2000), in which the whole system, both the heat transfer inside the furnace and the heating of the slabs, are calculated simultaneously using CFD. The geometry of the slabs is simplified as a sheet on the floor of the furnace. The simulation is done in a steady state, so they modify the energy conduction equation in the slab region to make it depend on space instead of time, and they use an average displacement speed of the slabs. This method produces good results when compared with experimental measurements of the energy distribution inside the furnace. A variation of this method is presented by Hsieh *et al.* (2008) and recently used by Mayr *et al.* (2017). The slabs are simplified again as a sheet passing through the furnace. However, the mass and energy transport are modeled taking the sheet to be a high viscosity fluid experiencing laminar flow at constant speed without wall shear stress. This method provides adequate accuracy while leading to low computational cost and easy implementation.

Some studies have focused on the combustion or combustion problem, while less emphasis has been placed on the transfer of heat between the flue gas and the charge (Keramida *et al.*, 2000; Liu *et al.*, 2014; Martín *et al.*, 2012; Steward and Cannon, 1971; Zashkova, 2008). Some simulation studies of the heating process for ingots, bars and slabs that are of rectangular or round section in a reheating furnace in rolling and steel installations, have been studied by Han *et al.* (2012); Kim and Kang (2009); Marlow (1996) and Steinboeck *et al.* (2011). In addition, mathematical models for the application of heat transfer were developed by Chakraborty *et al.* (2017); Kang and Rong (2006) and Yang *et al.* (2017).

In the present work, the main objective is to reduce heat transfer losses by evaluating the refractory lining, dimensions, and types of materials of the walls or layers. The heat rate is an indication of the possible heat losses, in other words, the energy that is emitted to the outside of the furnace and which will therefore need to contribute to maintaining the proper temperature inside the furnace. From intermediate layer temperatures and average temperatures, we can assess whether the materials support the existing technical requirements.

2. METHODOLOGY

2.1 Heat conduction model

When there is a temperature gradient in a body, experience shows that there is a transfer of energy from the high temperature region to the low temperature region. In other word, the energy was transferred by conduction and that the heat rate per unit area is proportional to the normal temperature gradient.

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \dot{q} = \rho c\frac{\partial T}{\partial t} \tag{1}$$

Eq. (1) is the one-dimensional heat conduction equation in anisotropic media. To treat the heat rate not only one-dimensional, it is necessary to consider the energy balance in a control volume, as shown in Fig. 1. Therefore, the general equation for three-dimensional heat conduction is:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \dot{q} = \rho c\frac{\partial T}{\partial t} \tag{2}$$

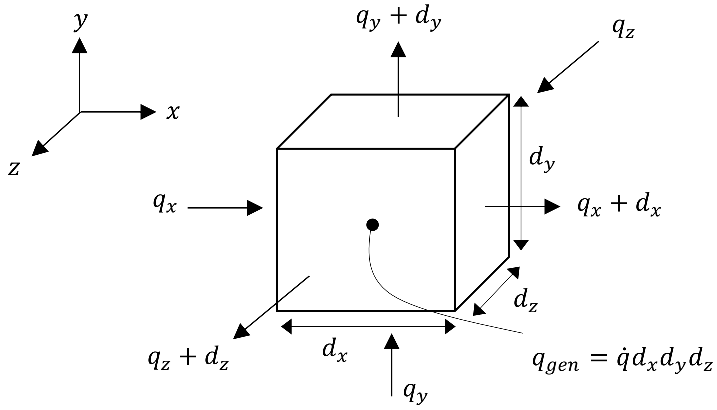

Figure 1. Elementary volume for the analysis of three-dimensional heat conduction in cartesian coordinates.

If the medium is isotropic, the thermal conductivity is independent of the position, Eq. (2) is written as Eq. (3), where $\alpha = \frac{k}{\rho c}$:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial \tau} \tag{3}$$

2.2 Entry conditions for the refractory lining calculation

Heat rate is understood as the process by which a heat source transmits heat through a solid wall to a cold medium. In view of the above considerations, the process can be divided into three parts: heat transfer from the hot medium to the wall, heat transfer through the wall, and heat transfer from the wall to the cold medium (Mariños *et al.*, 2020a).

For calculations, the values of the following magnitudes must be known:

- The internal temperature of the furnace (internal gas temperature), T_i.
- The environmental temperature after the outer wall of the furnace, T_e.
- The internal convective coefficient of thermal transfer, h_i.
- The external convective coefficient of heat transfer, h_e.
- The wall structure, taking into account its shape and thickness of the different coatings, Δx.
- The thermal conductivity coefficients of the materials and their variation with temperature, k.

With this data we should get:

- Heat rate, q".
- Temperatures on wall surfaces and in different coatings, T.

The process in which we are doing the study can be considered as a stationary process and its boundary conditions do not change over time.

The transfer of heat by unidimensional stationary conduction was used because the evaluation was carried out on the furnace walls similar to a flat plate study with multiple layers. And to simplify the problem, the following considerations were made.

- The furnace temperature is uniform,
- The temperature of the atmosphere is uniform and that is the same as the furnace temperature.
- The temperature of the gases inside the furnace is uniform and that is the same as the internal temperature of the furnace.
- The internal temperature of the furnace is uniform and the same as the temperature of the internal walls of the furnace.

Multi-layer transfer or series flat walls are developed if heat propagates through several walls in good thermal contact, and steady state heat rate analysis across all sections must be the same.

Figure 2 show the scheme for calculating the heat rate through a three-layer system where the temperature gradients are different.

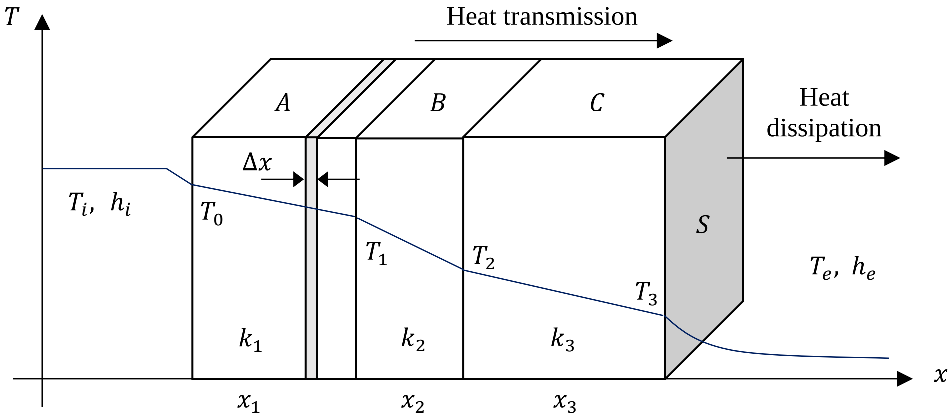

Figure 2. Heat transfer through a refractory lined wall in the furnace.

For the analysis of the refractory lining, as well as, obtaining the heat rate and temperatures on the wall surfaces of the different lining; the following equations will be used:

The steady state heat conduction is presented in Eq. (4) and (5). Dividing by Δx and tending Δx to zero, we obtain:

$$-\frac{dq"}{dx} = 0 \tag{4}$$

$$q"_1 = q"_2 = q"_3 = q" \tag{5}$$

By analyzing the heat rate, Eq. (6) is obtained:

$$q" = \frac{T_1 - T_2}{\left(\frac{x_1}{k_1}\right)_A} = \frac{T_2 - T_3}{\left(\frac{x_2}{k_2}\right)_B} = \frac{T_3 - T_4}{\left(\frac{x_3}{k_3}\right)_C} = \frac{T_1 - T_4}{\left(\frac{x_1}{k_1}\right)_A + \left(\frac{x_2}{k_2}\right)_B + \left(\frac{x_3}{k_3}\right)_C} \quad (6)$$

If a set of n layers is considered in perfect thermal contact, heat rate is defined as:

$$q" = \frac{T_1 - T_{n+1}}{\left(\frac{x_n}{K_n}\right)_i} \quad (7)$$

From Eq. (7), T_1 and T_{n+1} are the temperatures of layer 1 and the temperature of layer n, respectively.

The conditions were analyzed as a circuit as shown in Fig. 3, since more than one wall forms the structure. By first knowing the temperatures, the direction in which the flow is transmitted through the furnace structure must be observed, then the different parameters for the respective analysis are obtained.

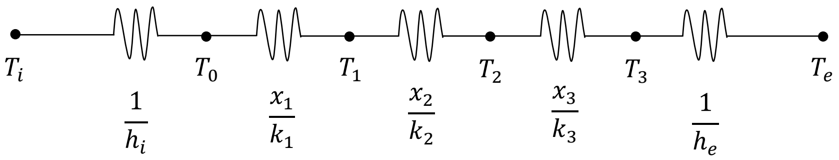

Figure 3. Thermal circuit through the reheat furnace layers.

The heat transmitted can be expressed for each section and, as is the same for all sections, can be set. For thermal conduction through the n layer walls, it is shown in Eq. (8):

$$q" = \frac{T_1 - T_{n+1}}{R_{eq}} \quad (8)$$

Where the value of the equivalent thermal resistance is described in Eq. (9):

$$R_{eq} = R_i + R_e + R_1 + R_2 + R_3 + R_n \quad (9)$$

The thermal resistance in each layer is determined by the ratio of coating thickness and thermal conductivity, except for the internal and external resistance which are determined by the inverse of the convective coefficient as shown in Eq. (10):

$$R_n = \frac{x_n}{k_n};\ R_i = \frac{1}{h_i};\ R_e = \frac{1}{h_e} \quad (10)$$

The specifications of each material must be recognized from the furnace design and the temperatures between the walls are also checked. Therefore, from Eq. (11), the temperature value in each furnace layer will be:

$$T_i - T_e = q"R_{eq} \quad (11)$$

Where, T_i and T_e are the furnace's internal and external temperatures, respectively.

3. RESULTS AND DISCUSSIONS

Normally the working temperature of a reheating furnace does not exceed 1200 °C. In this case, the working conditions for the furnace are shown in Tab. 1.

The physical parameters shown in Tab 1 were given by the hot strip rolling area of the steel industry located in the state of Espiritu Santo/SP - Brazil. The most important parameters are 11.72 hours of production and the productivity of 257 tons per hour. In the steel industry the following mixtures are employed: process gases coke oven (COG), steelmaking process (LDG), and blast furnace (BFG). Mixtures among these gases are also used: COG/BFG and COG/LDG (Mariños *et al.*, 2020b, 2020c).

The lining of the material must be anchored to the roof, walls and floor. Heat losses generated by radiation are not taken into account and, similarly, the emissivity coefficients will not be involved, this is due to the fact that the process will be analyzed as a unidimensional steady state process, through the analysis of the furnace walls as a flat plate study with multiple layers.

Table 1. Data for the determination of heat transfer in the reheating furnace of the steel industry.

Parameters	Specification	Units
For furnace		
Inside temperature of the walls	1200	°C
Outside temperature	27	°C
Outside temperature in layer (Mora, 2018)		
Roof	<85	°C
Walls	<95	°C
Floor	<95	°C
Thickness		
Roof	300	mm
Walls	300	mm
Floor	400	mm
Convection coefficients (Mora, 2018)		
Inside	700	W/m^2 °C
Outside	13	W/m^2 °C
Heat losses should not exceed (Mora, 2018)		
Roof	700	W/m^2
Walls	800	W/m^2
Floor	650	W/m^2
For production		
Productivity	257	t/h
Production time	11.72	h
For mixed gas		
Flow rate	30000	Nm^3/h
LHV (COG/LDG)	11769	kJ/Nm^3
LHV (COG/BFG)	9986	kJ/Nm^3
Specific mass (COG/LDG)	1.03	kg/Nm^3
Specific mass (COG/BFG)	0.98	kg/Nm^3

Convection coefficients were determined by Mora, based on several cases of continuous furnace refractory lining designs, and was corroborated by the ASTM-680 active standard that describes standard practice for estimate of the heat gain or loss and the surface temperatures of insulated flat, cylindrical, and spherical systems by use of computer programs. On the other hand, Mora (2018) presents the outside temperatures in the last layer and the maximum heat losses based on the technical specifications recommended by several manufacturers of continuous furnaces (Mariños *et al.*, 2020a).

The purpose of applying heat transfer in the reheating furnace is to quantify the heat lost by the furnace roof, walls and floor, as well as to quantify the temperatures in each layer. To reduce heat loss, coatings of several materials with a thickness in each layer and several configurations between them were used. The setting with the lowest heat loss represents the heat transfer losses in the furnace.

3.1 Distribution of materials in the roof, walls and floor of the reheating furnace

The materials employed in the coating are insulating materials such as refractories. For the roof, lightweight materials are used as the insulating concrete is low density and will always weigh more than a compacted ceramic fiber material.

For the walls, refractory materials with some mechanical strength are used in the first layer. Their mechanical strength should not be too high, but enough to prevent breakage in the event of blowouts due to billet. For the back layers low density materials such as silicates, fibers or microporous materials are employed. It is not very important to consider whether they are mechanically resistant or not, as they get covered by the refractory material (Mariños *et al.*, 2020a).

The most important area of the entire furnace in terms of coating is the floor, both the moving part and the fixed part. In this area a material with high mechanical strength is employed, as it will be in contact with the steel billet and will have to withstand lots of impacts. Subsequently, layers of insulating materials are placed to reduce their temperature as needed. Three types of materials employed can be differentiated: insulating panels (ceramics, silicate, and microporous fibers), insulating concrete, and refractory concrete.

For the calculation we need to distribute the materials on the roof, walls, and floor of the furnace as shown in Fig. 4. In the case of the roof 3 types of ceramic fiber module were evaluated, in the case of the walls 18 configurations were made, and in the case of the floor 5 configurations were evaluated.

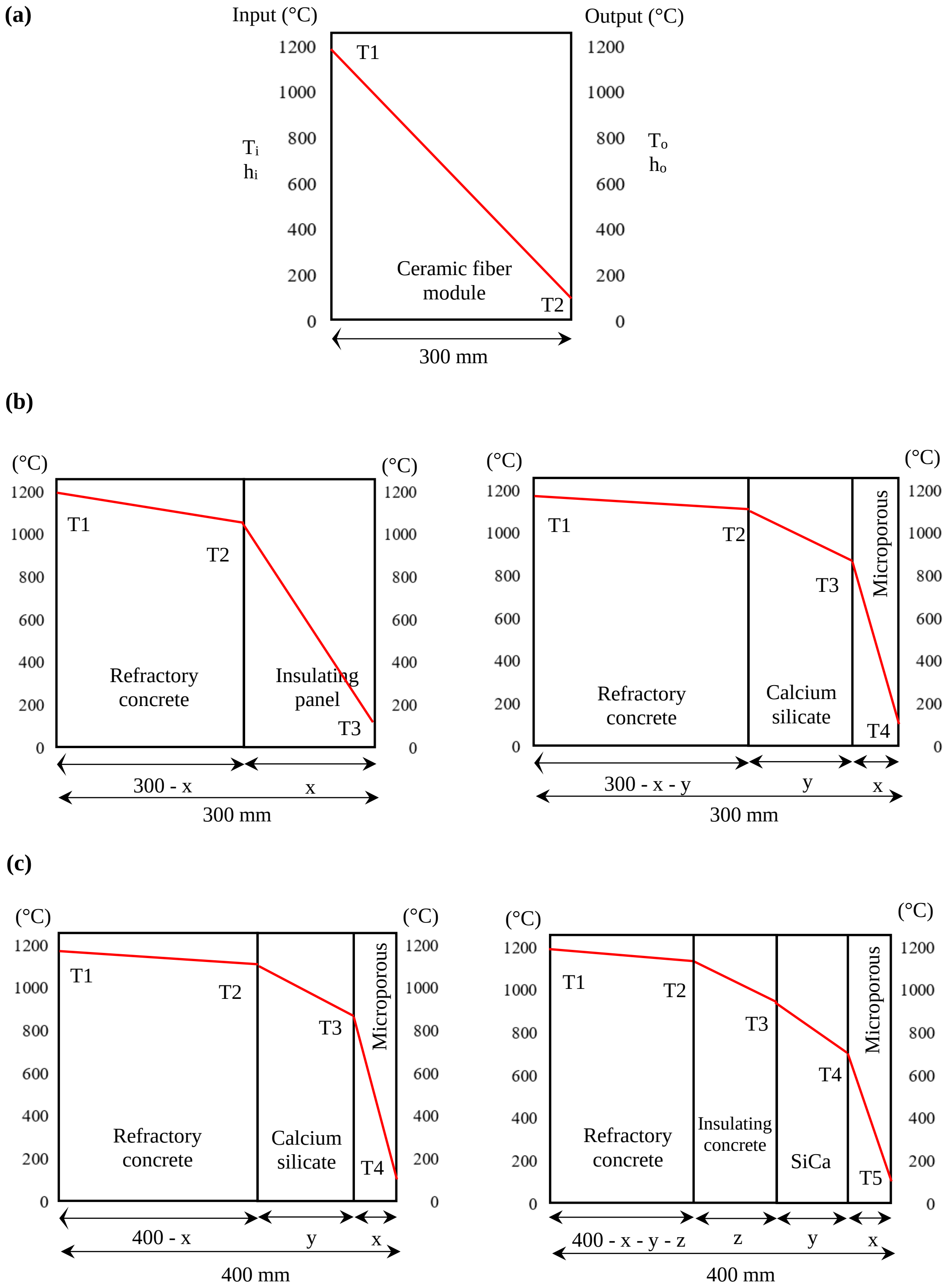

Figure 4. Coating of materials in the reheating furnace: (a) roof, (b) walls, and (c) floor.

3.2 Configuration of materials in the walls and floor of the reheating furnace

Knowing the conductivities of the materials, we established some configurations that determined the calculation; and is presented in Tabs 2 and 3.

Table 2. Material configurations in the furnace wall.

Materials	Configurations											
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Refractory concrete												
Hortix 1240	x	x	x	x								
Hortix 1260					x	x	x	x				
Hortix 1285									x	x	x	x
Insulating panel												
SiCa – 1000 °C	x				x				x			
SiCa – 1100 °C		x				x				x		
Microporous of 1000 °C			x				x				x	
Microporous of 1100 °C				x				x				x

Materials	Configurations					
	C13	C14	C15	C16	C17	C18
Refractory concrete						
Hortix 1240	x	x				
Hortix 1260			x	x		
Hortix 1285					x	x
Calcium silicate						
SiCa – 1100 °C	x	x	x	x	x	x
Microporous						
Microporous of 1000 °C	x		x		x	
Microporous of 1100 °C		x		x		x

Table 3. Material configurations in the furnace floor.

Materials	Configurations				
	L1	L2	L3	L4	L5
Refractory concrete					
Hortix 1285	x	x	x	x	x
Insulating concrete					
Horlite 1000		x	x		
Horlite 1.2.4.B				x	x
Calcium silicate					
SiCa – 1100 °C	x	x	x	x	x
Microporous					
Microporous of 1000 °C	x	x		x	
Microporous of 1100 °C			x		x

3.3 Results of temperature and heat in the roof, walls and floor of the reheating furnace

According to equations of section 2.2, and the data presented in Tab 1, we obtain the heat rate and temperature in each layer of materials.

Tables 4, 5 and 6 show the results of heat rate and temperature in each layer of the roof, walls and floor of the furnace, respectively.

Table 4. Results of heat rate and temperature in the roof layer of the reheating furnace.

Ceramic fiber module	q" (W/m^2)	Layer Temperature T_2 (°C)
160 kg/m^3	952.11	99.9
192 kg/m^3	813.45	89.2
240 kg/m^3	600.61	72.9

Table 5. Results of heat rate and temperature in the walls layers of the reheating furnace.

Layer materials	Configurations	q" (W/m^2)	T_1 (°C)	T_2 (°C)	T_3 (°C)	T_4 (°C)
Refractory concrete (200 mm) + Isolating panel (100 mm)	C1	1428.75	1197.9	976.4	136.3	-
	C2	1238.65	1198.2	1006.2	121.8	-
	C3	308.68	1199.5	1151.7	-	-
	C4	350.15	1199.5	1145.2	-	-
	C5	1505.78	1197.8	1027.6	-	-
	C6	1296.13	1198.1	1051.6	126.1	-
	C7	-				
	C8	-				
	C9	-				
	C10	-				
	C11	-				
	C12	-				
	C13	522.96	1199.2	1119.2	-	-
Refractory concrete (200 mm) + SiCa (75 mm) + Microporous (25 mm)	C13.1	801.23	1198.8	1076.2	802.9	88.2
	C14	851.23	1198.7	1068.5	778.2	92.1
	C15	824.89	1198.8	1007.2	-	-
	C16	877.99	1198.7	1101.2	-	-
	C17	843.28	1198.8	1131.3	-	-
	C18	898.85	1198.7	1126.8	-	-

Table 6. Results of heat rate and temperature in the floor layer of the reheating furnace.

Layer materials	Configurations	q" (W/m^2)	T_1 (°C)	T_2 (°C)	T_3 (°C)	T_4 (°C)	T_5 (°C)
Refractory concrete (200 mm) + Isolating panel (100 mm) + SiCa (75 mm) + Microporous (25mm)	L1	530.77	1199.2	1135.5	-	-	-
	L2	616.39	1199.1	1149.8	921.7	690.6	74.2
	L3	653.48	1199.0	1146.7	904.9	659.8	76.9
	L4	606.80	1199.1	1150.6	907.9	680.4	73.6
	L5	642.74	1199.0	1147.6	890.5	649.5	76.2

The configuration that was not calculated is due to the fact that T_2 exceeds the working temperature limit of the material.

A summary of the materials used in each layer of the roof, walls and fireplace of the reheating furnace is given in Fig. 5.

With the best setting we determine the heat lost by heat transfer through the furnace's roof, walls, and floor. To get the results in energy units, we multiply the heat by the furnace area. The results are presented in Tab. 7.

Table 7. Heat transfer through the roof, walls and floor of the reheating furnace.

Heat transfer	q" (W/m^2)	A (m^2)	$\dot{Q}$ (W)
Roof	600.61	676.65	406 402.76
Walls	801.23	937.26	750 960.83
Floor	606.80	676.65	410 591.22
Total			1 567 954.81

Using the production data from Tab. 1, such as productivity data and production time, we obtain the results of heat transfer losses for the COG/LDG and COG/BFG mixtures. Results are shown in Tab. 8.

To obtain the percentages of losses due to heat transfer it was divided between the heat supplied by the fuel (Mariños *et al.*, 2020a).

Table 8. Losses due to heat transfer for mixtures COG/LDG and COG/BFG.

Heat	COG/LDG	COG/BFG	Units
Heat lost by heat transfer	66.3	66.3	GJ
	22.2	22.2	MJ/ton
	1.6	1.9	%

The heat supplied by the fuel represents 100% of the input heat. It is also shown in Tab. 8 that the heat lost by heat transfer is very low, which means that the materials used in the furnace's roof, wall and floor layers are correct.

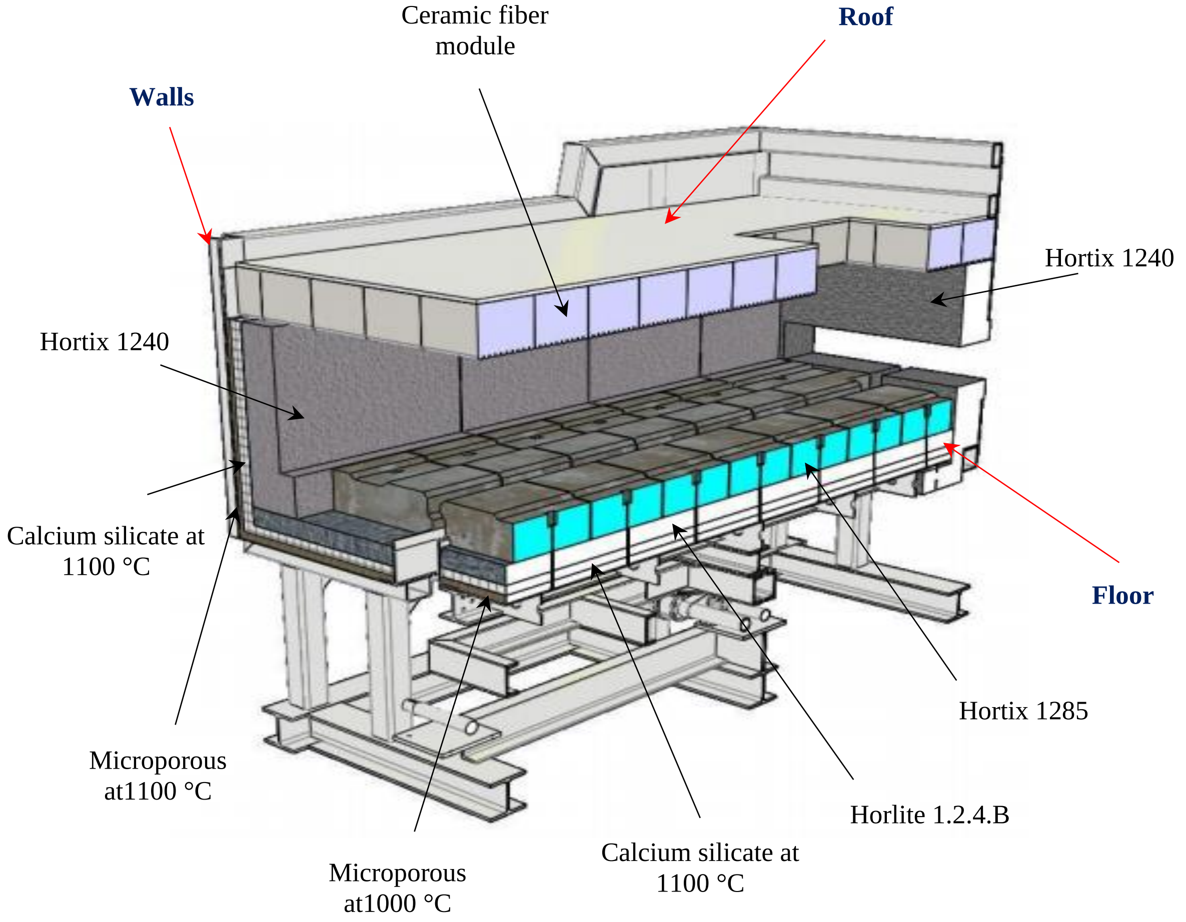

Figure 5. Cutting section to show the materials in the roof, walls and floor layers of the reheating furnace.

4. CONCLUSIONS

In order to reduce the heat transfer losses in the furnace below 2% in each case, an insulation analysis was performed on the roof, walls and floor of the furnace, taking into account the types of materials and thickness in each layer.

The best configuration for each case was selected. In the case of the roof, the third type of ceramic fiber module was used, which is 240 kg/m^3, since its heat values are low and the outside temperature is below the allowed temperature, which is < 85 °C with a heat rate of 600.61 W/m^2.

For walls, configuration 13.1 has been selected as the heat is lower than all other configurations. In this sense, the materials used in the furnace walls are 200 mm refractory concrete (Hortix 1240), plus 75 mm calcium silicate at 1100 °C, and 25 mm microporous at 1100 °C; obtaining 88.2 °C as the outer temperature of the layer, that is lower than the allowable temperature, which is < 95 °C with a heat rate of 801.23 W/m^2.

For the floor, the best configuration was L4 and the materials used are 200 mm refractory concrete (Hortix 1285), plus 100 mm insulating concrete (Horlite 1.2.4.B), plus 75 mm calcium silicate at 1100 °C, and 25 mm microporous at 1000 °C; obtaining the outer temperature of the layer as 73.6 °C, that is lower than the allowable temperature, which is < 95 °C with a heat rate of 606.80 W/m^2.

5. ACKNOWLEDGEMENTS

The authors are grateful to CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) and FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo) for support of this work through Project 2017/08975-1.

6. REFERENCES

Chakraborty, S., Rajora, A., Pal, S. and Talukdar, P., 2017. "Heat transfer and discrete phase modelling of coal combustion in a pusher type reheating furnace". *Applied Thermal Engineering*, Vol. 116, pp. 66–78.

Han, S., and Chang, D., 2012. "Optimum residence time analysis for a walking beam type reheating furnace". *International Journal of Heat and Mass Transfer*, Vol. 55, No. 15, pp. 4079–4087.

Hsieh, C., Huang, M., Lee, S. and Wang, C. 2008. "A coupled numerical study of slab temperature and gas temperature in the walking-beam-type slab reheating furnace". *Numerical Heat Transfer; Part A: Applications*, Vol. 54, No. 6, pp. 625–646.

Kang, J., and Rong, Y., 2006. "Modeling and simulation of load heating in heat treatment furnaces". *Journal of Materials Processing Technology*, Vol. 174, No. 3, pp. 109–114.

Keramida, E., Liakos, H., Founti, M., Boudouvis, A. and Markatos, N., 2000. "Radiative heat transfer in natural gas-fired furnaces". *International Journal of Heat and Mass Transfer*, Vol. 43, No. 10, pp. 1801–1809.

Kim, Y. D. and Kang, D. H., 2009. "Experimental and numerical studies on the thermal analysis of the plate in indirectly fired continuous heat treatment furnace". *Journal of Mechanical Science and Technology*, Vol. 23, pp. 631–642.

Li, Z., Barr, P. and Brimacombe, J., 1988. "Computer simulation of the slab reheating furnace". *Canadian Metallurgical Quarterly*, Vol. 27, No. 3, pp. 187–196.

Liu, H., Saffaripour, M., Mellin, P., Grip, C. E., Yang, W. and Blasiak, W., 2014. "A thermodynamic study of hot syngas impurities in steel reheating furnaces - corrosion and interaction with oxide scales". *Energy*, Vol. 77, pp. 352–361.

Marlow, D. O., 1996. "Modelling direct-fired annealing furnaces for transient operations". *Applied Mathematical Modelling*, Vol. 20, No. 1, pp. 34–40.

Mariños, D., Rojas, S., Carvalho, J. and Chucuya, R., 2019. "Comparison between the steam compression refrigeration system with intercooler and with compressor scale system: A case study". *Energy Conversion and Management*, Vol. 183, pp. 406–417.

Mariños, D., Rojas, S., Amaro, J., Mayworm, F., Carvalho, J. and Mendiburu, A., 2020a. "Energetic analysis of reheating furnaces in the combustion of coke oven gas, Linz-Donawitz gas and blast furnace gas in the steel industry". *Applied Thermal Engineering*, Vol. 169, pp. 114905.

Mariños, D., Rojas, S., Amaro, J., Carvalho, J., Mendiburu, A. and Chucuya, R., 2020b. "Reheating furnaces in the steel industry: Determination of the thermal powers in the combustion of Coke Oven Gas, Linz-Donawitz Gas and Blast Furnace Gas". In *Proceedings of the 18th Brazilian Congress of Thermal Sciences and Engineering*. RS, Brazil.

Mariños, D., Rojas, S., Amaro, J., Carvalho, J., Mendiburu, A. and Chucuya, R., 2020c. "Reheating furnaces in the steel industry: Utilization of combustion gases for load preheating and combustion air preheating using process gases COG, LDG and BFG". In *Proceedings of the 18th Brazilian Congress of Thermal Sciences and Engineering*. RS, Brazil.

Martín, E., Meis, M., Mourenza, C., Rivas, D. and Varas, F., 2012. "Fast solution of direct and inverse design problems concerning furnace operation conditions in steel industry". *Applied Thermal Engineering*, Vol. 47, pp. 41–53.

Mayr, B., Prieler, R., Demuth, M., Moderer, L. and Hochenauer, C., 2017. "CFD analysis of a pusher type reheating furnace and the billet heating characteristic". *Applied Thermal Engineering*, Vol. 115, pp. 986–994.

Mora, F., 2008. *Refractory lining in galloping hearth furnace*. Carlos III University of Madrid, Spain.

Steinboeck, A., Graichen, K., Wild, D., Kiefer, T. and Kugi, A., 2011. "Model-based trajectory planning, optimization, and open-loop control of a continuous slab reheating furnace". *Journal of Process Control*, Vol. 21, pp. 279–292.

Steward, F. R. and Cannon, P., 1971. "The calculation of radiative heat flux in a cylindrical furnace using the Monte Carlo Method". *International Journal of Heat and Mass Transfer*, Vol. 14, No. 2, pp. 245–262.

Trinks, W., Mawhinney, M., Shannon, R., Reed, R. and Garvey, J., 2004. *Industrial Furnaces*, John Wiley & Sons, New Jersey, 6th edition.

Venturino, M. and Rubini, P., 1995. "Coupled fluid flow and heat transfer analysis of steel reheat furnaces". In *Proceedings of the 3th European Conference on Industrial Furnaces and Boilers.* Lisbon, Portugal.

Yang, J., Cai, J., Sun, W. and Huang, J., 2017. "Optimal allocation of surplus gas and suitable capacity for buffer users in steel plant". *Applied Thermal Engineering*, Vol. 115, pp. 586–596.

Zhang, C. Ishii, T., Hino, Y. and Sugiyama, S., 2000. "The numerical and experimental study of non-premixed combustion flames in regenerative furnaces". *International Journal of Heat and Mass Transfer*, Vol. 122, pp. 287–293.

Zashkova, L., 2008. "Mathematical modelling of the heat behavior in the ceramic chamber furnaces at different temperature baking curves". *Simulation Modelling Practice and Theory*, Vol. 16, No. 10, pp. 1640–1658.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.