



encit 2020



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

ENC-2020-0016

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

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.marinosp@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 reheating furnace of the steel industry was evaluated in the present study, which uses the gas mixture from coke oven (COG), steelmaking process “Linz-Donawitz” (LDG) and blast furnace (BFG). The purpose of this article was to estimate the thermal powers at each stage of the reheating furnace process. Each case was analyzed for mixtures of COG/LDG and COG/BFG; obtaining the quantities of the following thermal powers: Heat supplied by the fuel, heat loss by heat transfer, heat absorbed by steel, heat of the combustion gases, heat for air preheating and other heat losses. The thermal powers obtained was presented in a Sankey diagram. In addition, to reduce losses by heat transfer in the furnace below 2% in each case. An analysis of insulation was carried out on the roof, walls and floor, taking into account the types of materials and thickness in each layer. It is evident that for the COG/LDG mixture, 46.7% of the heat transferred to the steel was obtained, and among the losses, 13.3% was obtained from the combustion gases, 1.6% from the heat transfer and 31.6% from other losses in the furnace, being a total of 46.5%. For the COG/BFG, the results obtained were similar.*

Keywords: *energy consumption, heat loss, thermal powers, reheating furnaces, steel industry.*

1. INTRODUCTION

Since the 1970s, due to the global energy crisis and the development of a high-speed rolling mill, modeling and control of reheating furnaces has received much attention (Hu *et al.*, 2018). Considerable progress was made since then by including applications of some sophisticated strategies for real-time furnace reheat control.

Continuous plate or billet reheating furnaces have an important performance in the area of hot strip rolling. These are where intermediate products, such as slabs or billets, are reheated until they become sufficiently plastic for subsequent processing (Luo and Yang, 2017).

The steel industry has grown a lot in its production, energy economy, product structure, and is an important industry in the world economy (Barmatov, 2017). The rapid growth of the industry is accompanied by huge energetic consumption, which happens in Brazil, in Europe, in China, and worldwide. Energy consumption by the steel industry represents between 10% and 15% of total energy consumption in the world (Chen *et al.*, 2018).

Reheating furnaces consume too much energy in the steel industry, in the same way that the refrigeration industry also consumes too much energy (Mariños *et al.*, 2019). These furnaces are used for heat treatment and reheating processes forming a metal powder and molding solidified products. Reheating furnaces represent 67% of the energy used in a steel industry. 31.36% of the total energy consumed by furnaces is expelled into the environment through combustion gases at temperatures of 800 to 900 °C (Johansson, 2013). The specific energy refers to energy consumed to heat a portion of the processed steel. Energy consumption is an indicator which is related with the carbon emissions and the operating costs (Gunarathne *et al.*, 2016).

One of the first studies that improved the efficiency of the reheating furnace was the work of Martensson (1992). Its methodology consisted of having a control of the furnace energy, determining the different thermal input and output powers at each stage of the process. Martensson's (1992) work consisted in determining the thermal powers supplied, used and lost in the reheating furnace processes. In this research, the author obtained in his results the heat supplied by the fuel which represented 100%, and the heat from iron oxidation of 3%. Among the thermal powers used by the furnace, the heat absorbed by the steel was 46%, the heat for preheating the air was 14% and the heat for the cooling water was 13%. In addition, it obtained a total heat loss of 44%, composed of flue gas losses (24%) and other losses (20%).

The objective of this research is to estimate the thermal powers at each stage of the reheating furnace process. The heat lost by combustion gases was also studied through the first law of thermodynamics. In addition, to reduce furnace heat transfer losses below 2%, an insulation analysis was performed on the furnace walls, taking into account the types of materials and thicknesses of each layer.

2. MATERIAL AND METHOD

2.1 System components for the production of steel plates

2.1.1 Walking beam reheating furnaces

The hot strip rolling of the steel industry located in the state of Espiritu Santo/SP - Brazil has 2 reheating furnaces of mobile beam steel plates with a capacity of 490 tons per hour of nominal production, each supplied with mixed gas. Currently, the average productivity is approximately 400 tons of plates per hour. The average outlet temperature of the carbon steel plate is approximately 1200 °C. Furnace 1 was chosen for the development of this work. The structure and characteristics of the furnace 2 are the same (Mariños *et al.*, 2020a, 2020c).

2.1.2 Production of steel plates

The plates enter the furnace at different temperatures, ranging from environmental temperature to 800 °C and are transported inside by a mobile beams system. The heating cycle inside the furnace is approximately 3 hours, from the plate entry to its exit.

2.1.3 Features of heat recuperator

The heat recuperator is a device that allows the recovery of part of the energy inside the combustion gases, through the mechanical ventilation system. This is done by means of an exchanger that puts into contact the internal gases that are extracted with the outside air that is introduced, without mixing the fluids of the two circuits.

The combustion air is reheated in the hearth located in the vertical duct of the reheating furnace. The hearth consists of 3 units and each unit consists of 3 tubes. The furnaces work with controlled combustion air between 0.95 - 1.05.

2.1.4 Characteristics of process gases

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 or COG/LDG. (Mariños *et al.*, 2020b, 2020c).

Coke oven gas (COG) contains high concentrations of methane and hydrogen and is generated during the coking of coal and iron ore. It has a calorific value of approximately half that of natural gas. The biggest consumer of this gas is the coke plant, which uses up to 50% as fuel. The COG goes through a cleaning process where dust, light oil, tar, naphthalene, sulfur compounds and the cracking of ammonia in hydrogen are removed. As it has a relatively high calorific value, it can be used alone or mixed with other gases in reheating furnaces of hot-band mills, coke ovens, blast furnace stoves, but also in annealing lines or power plants (Caillat, 2017).

Steelmaking process (LDG) or Basic Oxygen Furnace Gas (BOFG) is one of the most important secondary energy sources in the steel industry, which can be used directly as fuel for many production equipment, such as heaters and steam generators. LDG generation and consumption suffer from massive fluctuation that results in increased operating costs, environmental pollution and even a threat to proper production. LDG is generated as a result of the partial oxidation of carbon in liquid iron to carbon monoxide. In the period where the carbon monoxide concentration in the gas is sufficiently high (> 30 %), the gas is collected in a gasholder and can be valorized. The lowest heating value of BOFG is about a quarter of natural gas, this is usually saturated with water vapor (Caillat, 2017).

Blast furnace gas (BFG) generally contains about 1 to 8% of hydrogen and 19 to 27% of carbon monoxide, and a large amount of carbon dioxide and nitrogen. It can be relatively clean. The temperature of the adiabatic flame is too low to heat the product above 1200 °C, this is because it has a low caloric power between 2.6 and 4.0 MJ/Nm³, that is, about one tenth of the natural gas. Therefore, it is used in processes that involve low temperature, such as in coke ovens and hot jet stoves, or is often used with preheated air or enriched with natural gas or COG before being used as fuel.

2.2 Method for estimating heat losses in the reheating furnace

The development of the method to estimate heat loss in the furnace will be applied to 12 hours of productivity and will be analyzed for COG/LDG and COG/BFG mixtures. The heats to be evaluated are shown in Fig. 1 and consist of the following: heat supplied by fuel, heat lost by heat transfer in the furnace, heat absorbed by steel, heat from combustion gas, heat from air preheat, heat lost by combustion gases, heat from iron oxidation, heat from cooling water and other heat losses. Its formulation is presented in Eq. (1).

$$Q_{fuel} + Q_{iron\ oxidation} + Q_{air\ preheating} = Q_{cooling\ water} + Q_{absorbed\ by\ steel} + Q_{furnace\ heat\ transfer} + Q_{combustion\ gases} + Q_{other\ losses} \quad (1)$$

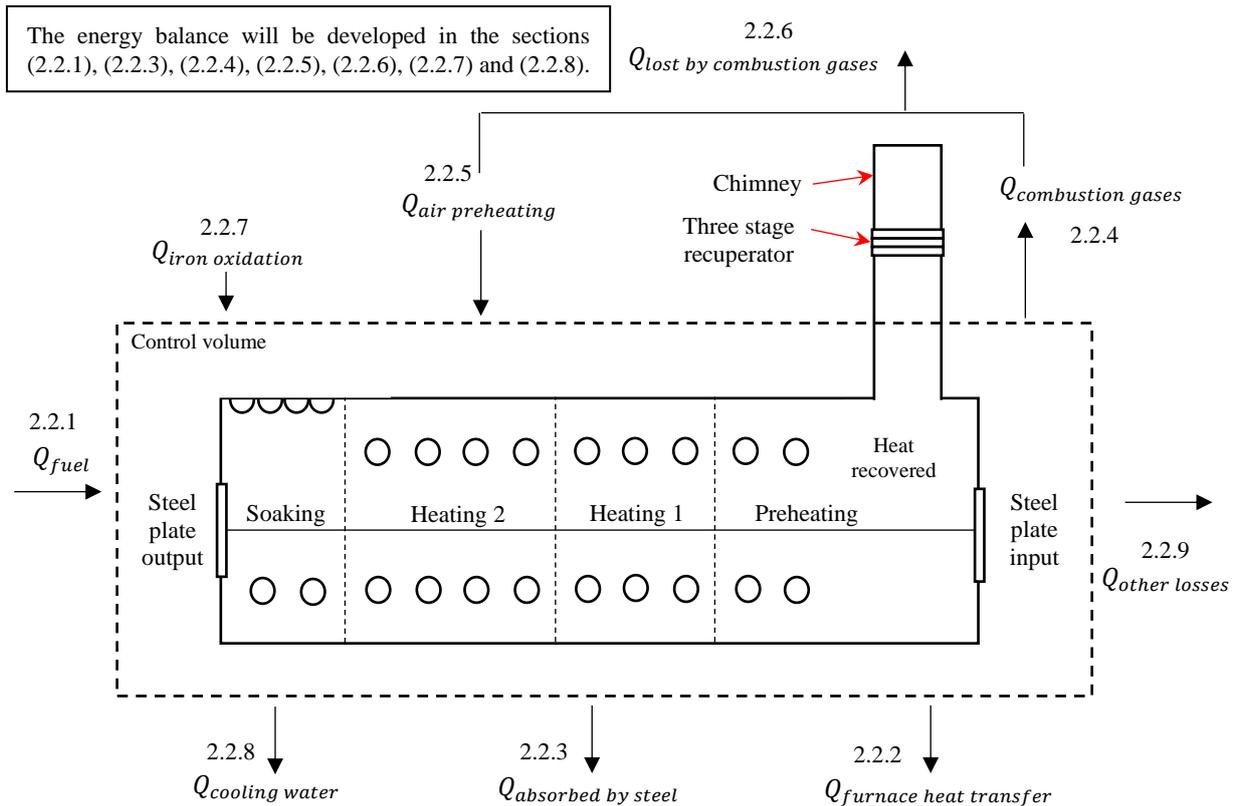


Figure 1. Method for estimating heat losses at each stage of the reheating furnace process.

2.2.1 Heat provided by the fuel

Heat provided by the fuel is the heat produced by the chemical reaction of the fuel with the oxidizer that is accompanied by energy release and usually manifests itself by incandescence or flame through the injectors. It is expressed as follows:

$$Q_f = LHV \dot{m}_f \quad (2)$$

To obtain the caloric rate in kJ/kg, it is divided by the mass flow of production. Eq. (2) is represented as follows:

$$Q_f = LHV \dot{V}_f \frac{1}{\dot{m}_{pro}} \quad (3)$$

From Eq. (3), Q_f is the heat provided by the fuel and \dot{m}_{pro} is the productivity.

2.2.2 Furnace heat transfer

Heat transfer will be used to quantify the heat lost by conduction through the furnace walls. An evaluation will be carried out to determine materials that allows obtaining the minimum transfer of heat and temperature to the outside.

A more exhaustive methodology to evaluate the heat transfer in the furnace was developed and presented by Mariños *et al.* (2020a, 2020b) from which the results that will complement this work will be obtained.

2.2.3 Heat absorbed by steel

Heat absorbed by steel is the heat used by steel to heat the plate from an initial temperature to a final temperature. It is obtained with Eq. (4).

$$Q_s = m_s C_{p_s} \Delta T_s \quad (4)$$

To obtain the mass of the plates we multiply the productivity with the production time. Eq. (5) is expressed as follows:

$$Q_s = \dot{m}_{pro} \Delta t C_{p_s} \Delta T_s \quad (5)$$

From Eq. (5), ΔT_s is the temperature variation of steel plates. Energy balance first requires determination of the heat transferred to the plates, which requires knowledge of the specific heat of the steel.

2.2.3.1 Model for specific heat of steel

To obtain the specific heat of steel, we have to know the heat used by the steel plates and apply the model developed by Prieto *et al.* (2001). Eq. (6) shows the specific heat depending on the temperature.

$$\bar{C}_p = \frac{1}{\Delta T} \int_{T_1}^{T_2} C_p(T) dT \quad (6)$$

The model of Prieto *et al.* (2001), presents a graph that shows different curves of the specific heat of steel as a function of temperature. These curves are within a temperature range that influences the increase or decrease of specific heat.

To get an approximation of the heat transferred to the steel plates, we employed Martensson's Sankey Diagram (1992), which determines that the plates use a 46% of the energy that enters the reheating furnace.

Martensson's Sankey Diagram shows the results of heat loss and use at several stages of the process of a continuous furnace. It presents the heats provided by the fuel, the heat of oxidation of the plates, the heat of the preheated air, the heat of the cold water and the combustion gases, as well as the heat transferred to the steel, among other losses. Martensson determined that steel plates take advantage of 46% of the total heat entering the furnace. This result was used to estimate the heat used by the steel plate in Mcal/t and determine the specific heat of the steel for different temperature ranges.

To know the heat transferred to the steel plates, two trials were accomplished, one for each fuel mixture (COG/LDG and COG/BFG). For this we needed the heat of the fuel that was determined by Eq. (3). The heat obtained was 1766 MJ/t and 1498 MJ/t for the COG/LDG and COG/BFG mixtures for a volumetric flow of 30000 Nm³/h of fuel.

Two attempts were made following the model of Prieto *et al.* (2001). With the aim of reaching the value of 812 MJ/t and 689 MJ/t representing 46% of the energy for each mixture, respectively, for the temperature range of 10 to 1200 °C. Table 1 shows the specific heat and heat transferred from the steel at the different temperature ranges.

Table 1. Specific heat and heat transferred from steel at different temperature ranges. Enter the temperature values in °C.

Temperature (°C)	C _p (J/kg °C)		ΔH (J/kg)	
	a	b	a	b
COG/LDG				
10 – 350	600	0	600	0
350 – 650	308.33	0.83	308.33	0.42
650 – 730	- 206.25	1.63	- 206.25	0.81
730 – 800	4421.40	-4.71	4421.40	- 2.36
800 – 1200	650	0	650	0
COG/BFG				
10 – 500	550	0	550	0
500 – 680	272.22	0.56	272.22	0.28
680 – 700	- 4450	7.50	- 4450	3.75
700 – 750	5466.70	- 6.67	5466.70	- 3.30
750 – 1200	600	0	600	0

From Eq. (6) we obtain the specific heat of steel presented by Eq. (7), and by integrating it we obtain the heat transfer of the steel shown in Eq. (8).

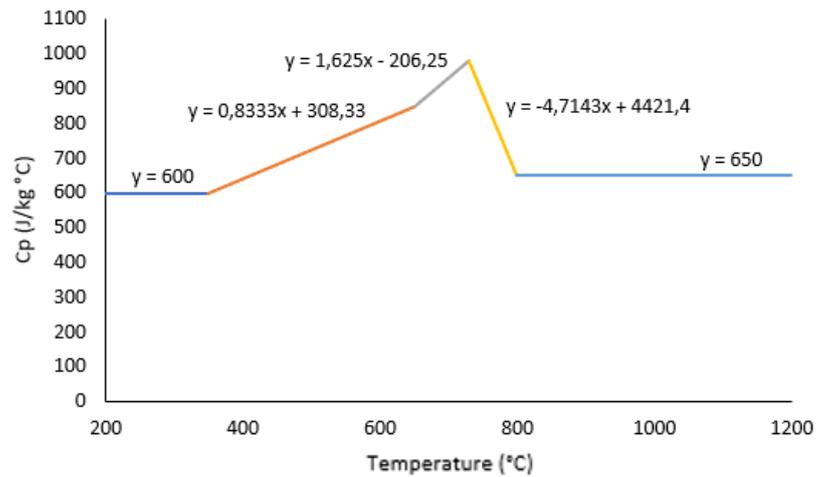
$$C_p = a + bT \quad (7)$$

$$\Delta H = a(T_2 - T_1) + b(T_2^2 - T_1^2) \quad (8)$$

The data for the coefficients of Eqs. (7) and (8) are presented in Tab. 1.

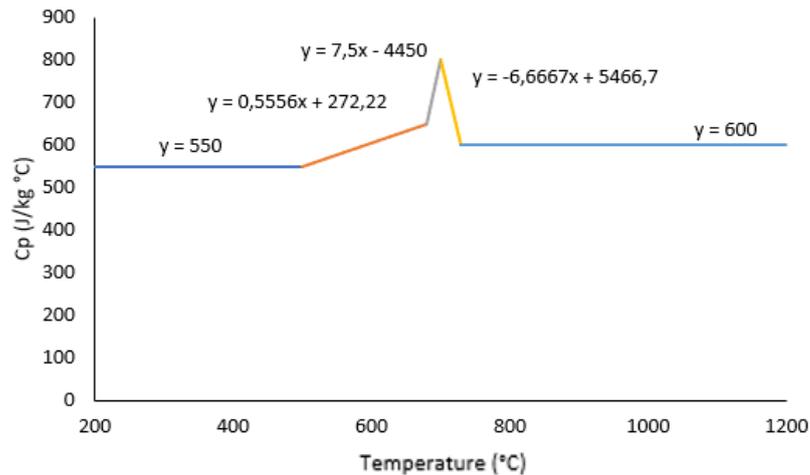
To determine the data presented in Tab. 1, some curves were made on the model provided by Prieto *et al.* (2001) maintaining the proportions of the specific heat in each range, in order to reach the heats of 812 MJ/t and 689 MJ/t used by the steel plates for each fuel mixture. The curves were performed in a calculation software, and its results are shown in Fig. 2.

(a) Steel specific heat: COG/LDG



Heat transferred to steel **812 MJ/t**

(b) Steel specific heat: COG/BFG



Heat transferred to steel **689 MJ/t**

Figure 2. Attempt to approximate the specific heat of the steel for the different temperature ranges of the mixtures:
(a) COG/LDG and (b) COG/BFG.

2.2.4 Heat of combustion gases

Heat of combustion gases is the heat of combustion products emitted into the atmosphere as a consequence of the chemical reaction between the fuel and air. The steel industry generates huge amounts of combustion gas through the chimney of COG, LDG, and BFG reheat furnaces. The goal is to harness the residual heat from the combustion gases from the reheat furnace chimney by applying a technology such as the heat recuperator to recover unused energy content through these effluents, and thus meet a site's need such as preheating of combustion air (Mariños *et al.*, 2020a).

There are two ways to quantify the heat of combustion gases, the first is through the use of Eq. (9) and the second is through the energy balance procedure applying the adiabatic flame temperature.

$$Q_g = m_g C_{p,g} (T_g - T_a) \quad (9)$$

We employed the energy balance procedure to determine the stoichiometric reaction and obtain the adiabatic flame temperature. The same equation was used to obtain the enthalpy variation (ΔH) as a function of gas temperature. Knowing the variation of gas enthalpy divided by the LHV of the fuel mixture, we obtained the percentage of heat emitted to the atmosphere. On the other hand, knowing the temperature of the chimney heat recuperator and substituting in the enthalpy variation equation we obtained the percentage of heat used by the heat recovery that is used for the preheating of the combustion air.

2.2.4.1 Adiabatic flame temperature

The adiabatic flame temperature for the combustion gases can be determined by the energy balance shown in the following equation (Carvalho and McQuay, 2004):

$$\text{LHV} = \int_{T_i}^{T_f} [\sum_i n_i c_{p,i}] dT \quad (10)$$

From Eq. (10), n_i is the number of moles of gaseous components of combustion products. The energy equation is applied to the perfect gas, according to the first principle of thermodynamics.

2.2.4.2 Stoichiometric reaction general equation

In each part of the Eq. (11) there are reagents and products.



Where, α is the excess air, $(\text{O}_2 + 3.76 \text{N}_2)$ is the air composition for complete combustion, $\text{CO}_2, \text{H}_2\text{O}, \text{SO}_2, \text{O}_2, \text{N}_2$ are the products obtained after combustion and (a, b, c, d, e, f) are the indexes to get the stoichiometric balance.

The variation of enthalpy (ΔH) for a temperature range from T_i to T_g , where T_g is the gas temperature. The variation of enthalpy is given by Eq. (12) proposed by Carvalho and McQuay (2004):

$$\Delta H = \int_{T_i}^{T_f} [\sum_i n_i c_{p,i}] dT \quad (12)$$

This parameter is important because $\Delta H/\text{LHV}$ represents the percentage of energy lost to combustion gases at a temperature T_f .

From Eq. (12) and the coefficients of chemical Eq. (11), we obtain:

$$\Delta H_{\text{mixed gas}} + \int_{T_i}^{T_f} \alpha a [C_{p,\text{O}_2} + 3.76 C_{p,\text{N}_2}] dT = \int_{T_i}^{T_f} [b C_{p,\text{CO}_2} + c C_{p,\text{H}_2\text{O}} + d C_{p,\text{SO}_2} + e C_{p,\text{O}_2} + f C_{p,\text{N}_2}] dT \quad (13)$$

From Eq. (13), $\Delta H_{\text{mixed gas}}$ is the combustion enthalpy of the mixed gas composition COG/LDG and COG/BFG, and $C_{p,\text{CO}_2}, C_{p,\text{H}_2\text{O}}, C_{p,\text{SO}_2}, C_{p,\text{O}_2}$ e C_{p,N_2} are the specific heat at constant pressure of the combustion products.

Reagent and product values can be found from the stoichiometric reaction equation. Therefore, the only variable to be determined in Eq. (13) is the adiabatic flame temperature T_f .

The necessary parameters such as the specific heats at constant pressure of some substances and the thermodynamic properties for the calculation of adiabatic flame temperature are presented by Perry and Chilton (1973).

2.2.5 Heat used by air preheating

The heat gain through the enthalpy of the air warmed from an initial temperature T_i (here considered as 300 K) to a temperature T_f , after the combustion reaction to the mixed gas, is provided in Eq. (14):

$$\Delta H_{\text{air}} = \alpha \int_{T_1}^T [a_1 C_{p,O_2} + a_2 C_{p,N_2}] dT \quad (14)$$

A three-stage heat exchanger installed in the chimney is used in the steel industry. The recovered heat is directed to preheat the combustion air. The combustion air temperature at the stove outlet is 560 °C.

Obtaining the air enthalpy variation (ΔH_{air}) and dividing the LHV of the fuel mixture gives the percentage of heat recovered by combustion air preheating.

2.2.6 Heat lost by combustion gases

Heat lost by combustion gases is described as a part of the heat of combustion gases that cannot be recovered, which is defined as the total heat of the combustion gases minus the heat used by the heat exchanger installed in the furnace chimney. It is presented in Eq. (15):

$$Q_{\text{lg}} = Q_{\text{g}} - Q_{\text{air}} \quad (15)$$

2.2.7 Heat of iron oxidation

The heat gain through enthalpy for iron oxidation according to Eq. (16) is:

$$Q_i = (\eta_{\text{rust}} \dot{m}_s \Delta t) \Delta H_r \quad (16)$$

Where, η_{rust} is the rust fraction formed, \dot{m}_s is the mass flow of the plates inside the furnace, Δt is the time interval and $\Delta H_{\text{reaction}}$ is the oxidizing enthalpy of iron.

The reaction was considered $\text{Fe} + \frac{1}{2} \text{O}_2 \rightarrow \text{FeO}$, for which $\Delta H_{\text{reação}} = -272 \text{ kJ/mol}$. Substitute for reaction. The molecular weight of Fe is 55.85 g/mol.

2.2.8 Heat of cooling water

Heat loss for cooling water is defined in Eq. (17):

$$Q_w = (\dot{m}_w \Delta t) C_{p_w} \Delta T_w \quad (17)$$

2.2.9 Other heat losses

Other heat losses are the heat lost through the process and is quantified as the difference between the incoming and projecting heat at each stage of the reheat furnace process. It is determined with Eq. (1).

3. RESULTS AND DISCUSSIONS

The physical parameters shown in Tab. 2 were given by the hot strip rolling area of the steel industry located in the state of Espírito Santo/SP - Brazil. The most important parameters are 11.72 hours of production and the productivity of 257 tons per hour (Mariños *et al.*, 2020a, 2020b). The equations developed in section 2 will be applied.

3.1 Results of the estimate of heat losses in the reheating furnace

Using the production and mixed gas data from Tab. 2, and the equations developed in section 2, results presented in Tab. 3 are obtained.

In Tab. 3, it is observed that the heat provided by the COG/LDG mixture is greater than the heat provided by the COG/BFG mixture. This is because the LHV of the LDG is greater than the LHV of the BFG.

The heat supplied by the fuel represents 100% of the input heat. It is also shown in Tab. 3 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 (Mariños *et al.*, 2020b).

In addition, it is observed that the heat absorbed by steel from the COG/LDG and COG/BFG mixtures are the same, because the heat needed by the plates to achieve productivity is the same regardless of the type of fuel used. On the other hand, the combustion gases losses are obtained by the difference of the total combustion gas heat and the heat used by the heat exchanger installed in the reheat furnace chimney. These losses involve the heat lost by the reaction in some endothermic dissociations, the heat lost by the furnace efficiency, and the heat used by other equipment.

Table 2. Data to estimate thermal powers in the reheating furnace of the steel industry.

Parameters	Specification	Units
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
For steel plates		
C _p s [Obtained by Eq. (7)]	630	J/kg K
T _{initial} /T _{final}	200/1217	°C
For combustion gases		
T _g	840	°C
C _p g	1.147	kJ/kg K
For air		
Excess air (α)	5	%
T _{initial} /T _{final}	27/560	°C
C _p a	1.009	kJ/kg K
Specific mass	1.1614	kg/m ³
For iron oxidation		
Rust formation (Carvalho, 2015)	0.8	%
ΔH _{reaction}	-272	kJ/mol
For cooling water		
Flow rate	1066	Nm ³ /h
T _{initial} /T _{final}	28/35.6	°C

Table 3. Thermal powers at each stage of the reheating furnace process for fuel mixtures.

Heats	COG/LDG	COG/BFG	Units
Heat supplied by fuel	4138	3511	GJ
	1373	1164	MJ/t
Heat lost by heat transfer (Mariños <i>et al.</i> , 2020b)	66.3	66.3	GJ
	22.2	22.2	MJ/t
Heat absorbed by steel	1933	1933	GJ
	641	641	MJ/t
Heat of combustion gases	1501	1414	GJ
	498	469	MJ/t
Heat for air preheating	959	897	GJ
	318	297	MJ/t
Heat lost by combustion gases	542	518	GJ
	184	172	MJ/t
Heat of iron oxidation	118	118	GJ
	37.7	37.7	MJ/t
Heat of cooling water	398	398	GJ
	134	134	MJ/t
Other heat losses	1308	2001	GJ
	435	239	MJ/t

The Sankey diagram of the Fig. 3 shows the thermal powers at each stage of the reheating furnace process for the COG/LDG mixture.

The Sankey Diagram Table shows all previously obtained heats in percentages; In addition, it is observed that the heat used by the steel plates in the cases analyzed is 46.7% and 55.1% respectively, and the total lost heat composed by the combustion gases losses, heat transfer losses and other losses is 46.5% and 37% for each case.

The heat absorbed by steel is 46.7% and 55.1% for each fuel mixture, values that are very close to that obtained by Martensson (1992) which was 46%. This shows the effectiveness of the procedure performed and supports the considerations made at each stage of the process.

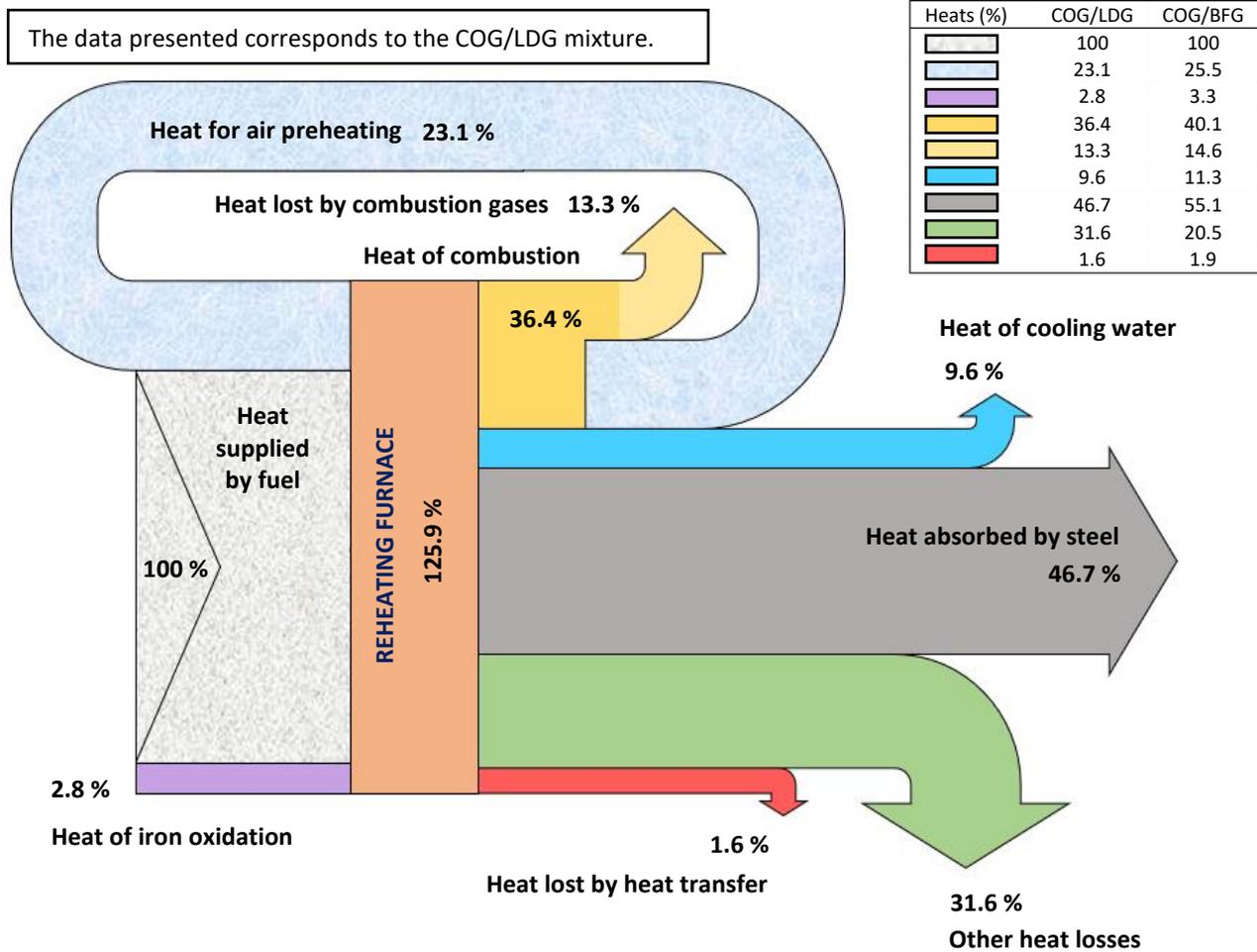


Figure 3. Sankey diagram to estimate the thermal powers at each stage of the reheating furnace process.

3.1.1 Validation of the method of estimating thermal powers in the reheating furnace

The validation of the thermal powers estimation method at each stage of the furnace process will be performed by comparing the results presented in the Sankey diagram of Fig. 3 with the results obtained by Martensson (1992). The comparison is presented in Tab. 4.

Table 4. Validation of the method of estimating thermal powers at each stage of the reheating furnace process.

Heats	COG/LDG mixture results	Martensson (1992) results	Units
Heat supplied by fuel	100	100	%
Heat lost by heat transfer	1.6	-	%
Heat absorbed by steel	46.7	46	%
Heat of combustion gases	36.4	38	%
Heat for air preheating	23.1	14	%
Heat lost by combustion gases	<u>13.3</u>	<u>24</u>	%
Heat of iron oxidation	2.8	3	%
Heat of cooling water	9.6	13	%
Other heat losses	<u>31.6</u>	<u>20</u>	%

Table 4 shows the results of the comparison, and it is observed that the total losses heat composed for the combustion gases losses, heat transfer losses and other losses is 46.5%, while Martensson obtained a total loss of 44%.

Apparently, our results show that in other losses it was 31.6% while Martensson (1992) obtained 20%, that is because in our case the industry has a greater use of heat for preheating the air, taking advantage of 23.1% of 36.4% of heat of flue gases. On the other hand, Martensson took advantage of 14% of 38% of the heat of the flue gases. The case analyzed for the COG/LDG mixture presents an income of 125.9% of energy to the furnace compared to the results of Martensson (1992) which presents an income of energy to the furnace of 117%. While the energy entering the furnace increases, the losses will also increase.

4. CONCLUSIONS

The method developed in this work was the basis for estimating the thermal powers at each stage of the process. Final results were presented in a Sankey diagram. It was analyzed for a productivity of 257 t/h and a time of 11.72 h. Obtaining 46.7% of heat transferred to steel, with a total loss of 46.5%, with data from the COG/LDG mixture. On the other hand, for the COG/BFG mixture, 55.1% of heat transferred to steel was obtained with a total loss of 37.0%, lower values than the COG/LDG mixture.

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

- Barmatov, E. and Hughes, T., 2017. "Effect of corrosion products and turbulent flow on inhibition efficiency of propargyl alcohol on AISI 1018 mild carbon steel in 4 M hydrochloric acid". *Corrosion Science*, Vol. 123, pp. 170–181.
- Caillat, S., 2017. "Burners in the steel industry: Utilization of by-product combustion gases in reheating furnaces and annealing lines". *Energy Procedia*, Vol. 120, pp. 20–27.
- Carvalho, J. A. and McQuay, M. 2004. *Princípios da Combustão Aplicada*, Ufsc, Florianópolis, Brazil, 1st edition.
- Chen, D., Lu, B., Dai, F., Chen, G. and Yu, W., 2018. "Variations on billet gas consumption intensity of reheating furnace in different production states". *Applied Thermal Engineering*, Vol. 129, pp. 1058–1067.
- Gunarathne, D., Mellin, P., Yang, W., Pettersson, M. and Ljunggren, R., 2016. "Performance of an effectively integrated biomass multi-stage gasification system and a steel industry heat treatment furnace". *Applied Energy*, Vol. 170, pp. 353–361.
- Hu, Y., Tan, C., Broughton, J., Roach, P. and Varga, L., 2018. "Nonlinear dynamic simulation and control of large-scale reheating furnace operations using a zone method-based model". *Applied Thermal Engineering*, Vol. 135, pp. 41–53.
- Johansson, M. T., 2013. "Bio-synthetic natural gas as fuel in steel industry reheating furnaces: A case study of economic performance and effects on global CO₂ emissions". *Energy*, Vol. 57, pp. 699–708.
- Luo, X. and Yang, Z., 2017. "A new approach for estimation of total heat exchange factor in reheating furnace by solving an inverse heat conduction problem". *International Journal of Heat and Mass Transfer*, Vol. 112, pp. 1062–1071.
- 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: reduction of heat transfer losses by analyzing the types of insulation materials and thickness in each layer". 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.
- Martensson, A., 1992. "Energy Efficiency Improvement by measurement and control, a case study of reheating furnaces in the steel industry". In *Proceedings of the 14th National Industrial Energy Technology Conference*. Houston, Texas, pp. 236 – 243.
- Perry, R.E. and Chilton, C.H. 1973. *Chemical Engineers' Handbook*, McGraw-Hill Book Company.
- Prieto, M., Ruiz, L. and Menendez, J., 2001. "Thermal performance of numerical model of hot strip mill runout table, Iron mark". *Steelmaker*. Vol. 28, pp. 474–480.

7. RESPONSIBILITY NOTICE

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