EXERGY BALANCE ON AN INDUSTRIAL CERAMIC TILE KILN

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1. ABSTRACT

Exergy is a thermodynamic concept which, put simply, may be defined as the energy capable of transforming itself into useful work. Therefore, it can be used to quantify energy quality. This paper presents the results obtained from an exergy balance on a ceramic tile firing kiln during the production of a porcelain stoneware tile composition. Exergy analysis allows identification and quantification of irreversibilities in the process or sources of exergy destruction, which show how to improve the functioning of a system in order to enhance process energy efficiency. In the kiln studied, the exergy destroyed due to irreversibilities amounted to 63% of the exergy contributed to the kiln, while only 8.5% of the exergy was used for physical-chemical transformation of the material, leaving about 28% of the remaining exergy for possible use. The results of the study show that the exergy performance of the kiln was mainly affected by the exergy destroyed during natural gas combustion, during the physical-chemical transformations of the material and during heat transfer. The application of this analysis method and the results obtained have allowed certain courses of action aimed at improving kiln efficiency to be addressed.

2. INTRODUCTION

In industrial ceramic kilns, energy analyses are based on the first law of thermodynamics, and in general, just involve enthalpy and heat balances. These balances, which are perfectly valid, enable determination of the amount of energy contained in each of the streams involved in the process. However, the information provided by these balances is limited by the fact that all the energy is quantified identically, without taking into account the energy degradation during its transformation. Therefore, such balances do not evaluate the quality of the energy contributed to the process or the energy remaining, which is very important to establishing possible future uses. Consequently, to study energy quality, the second principle of thermodynamics is used, which states that any thermal energy exchange process always involves loss in the ability to produce work (energy quality).

The concept of exergy is used to combine the first and second principles of thermodynamics, exergy being defined as the maximum useful work that could be obtained on taking a system, or given energy flow, from its original state to a state of thermodynamic equilibrium with the reference environment.

The exergy balance is obtained by combining energy and entropy balances, i.e. simultaneously applying the first and second principles of thermodynamics. This balance allows an analysis that describes the quality of the exchanged energies, as well as the ability of the systems to produce useful work, to be performed.

Application of an exergy balance to an open system, such as an industrial tile kiln, may be schematized in the manner shown in figure 1, in which there are input and output streams, work produced by or for the system (assumed to be negligible), and some heat flows to or from the system.

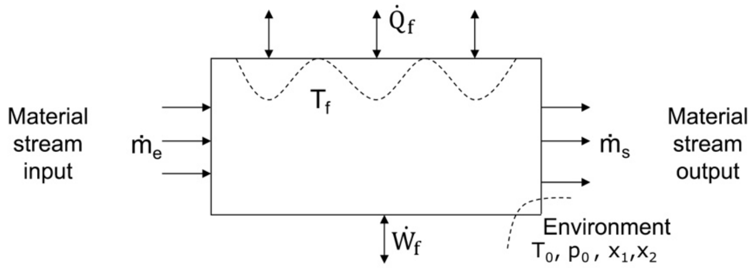

Figure 1. *Diagram of a control volume for the calculation of an exergy balance.*

The general expression of an exergy balance, for an open system in a steady state, is given by (Moran and Shapiro, 2006):

$$0 = \sum_i \dot{A}_{e,i} - \sum_i \dot{A}_{s,i} + \dot{A}_{Qf} - \dot{A}_D \qquad (1)$$

Where the first two terms of the second part of the equation correspond to the flow exergy associated with the input ($\dot{A}_{e,i}$) and output ($\dot{A}_{s,i}$) streams, while the term $\dot{A}_{Qf}$ corresponds to the exergy associated with heat flows lost through system surfaces. The term $\dot{A}_D$ corresponds to the exergy destroyed in the process associated with the system's thermodynamic irreversibilities.

In order to perform exergy calculations, it is necessary to define an environment used as a reference, i.e. one that has a known temperature, pressure and chemical composition, since exergy will always depend on the conditions of the system and the environment. For this, a stable reference area (SRA) is established, usually with the intensive variables T_0 (298 K) and p_0 (1 atm), comprised of various reference substances existing in the natural environment.

The standard reference environment for exergy used in the calculations in this study is that proposed by Szargut (Szargut, 2005).

2.1. EXERGY OF A MATERIAL FLOW ($\dot{A}_{E,I}$,$\dot{A}_{S,I}$)

A material's flow exergy may be divided into several components: kinetic, potential, physical (thermal and mechanical) and chemical exergy.

When a system is subjected to a process without significant changes in velocity and height between input and output conditions, kinetic exergy and potential exergy may be disregarded. This is the case for most processes. Disregarding kinetic and potential exergy, physical exergy and chemical exergy become the two main contributors.

As a result, the total exergy of a material flow in given conditions is expressed as the sum of physical exergy and chemical exergy.

$$\dot{A}_i = \dot{A}_f + \dot{A}_q \tag{2}$$

where $\dot{A}_f$ corresponds to physical exergy and $\dot{A}_q$ to chemical exergy.

- Physical and chemical exergy may be defined as follows:
- **Physical exergy** is the work attainable by subjecting a substance to reversible physical processes from its initial temperature and pressure, up to the pressure and temperature of the environment. This is the exergy attributable to the difference in temperature and pressure between the stream and the reference environment.
- **Chemical exergy** is the work attainable from a substance that is at the same pressure and temperature as the environment, if it reaches a state of thermodynamic equilibrium through chemical reactions. This is the exergy resulting from the difference in composition (chemical potential) between the system and the reference environment.

Therefore, the physical exergy of flow is given by the following expression:

$$\dot{A}_f = (\dot{H} - \dot{H}_0) - T_0(\dot{S} - \dot{S}_0) \tag{3}$$

Where $(\dot{H} - \dot{H}_0)$ is the change in enthalpy, and $(\dot{S} - \dot{S}_0)$ is the change in entropy, which may be obtained from data tabulated in thermodynamic tables (Çengel and Boles, 2006) at the corresponding temperature T and pressure P, taking into account the reference environment (Szargut, 1986 and 2005). When it is possible to consider the constant specific heat, the following equations may be applied to obtain the changes in enthalpy and entropy.

$$(\dot{H} - \dot{H}_0) = \frac{\dot{m}_i}{M_i} \cdot \left[c_{pi} \cdot (T - T_0)\right] \tag{4}$$

$$(\dot{S} - \dot{S}_0) = \frac{\dot{m}_i}{M_i} \cdot \left[c_{pi} \cdot \ln\left(\frac{T}{T_0}\right) - R \cdot \ln\left(\frac{p}{p_0}\right)\right] \qquad (5)$$

In these equations, the term $\dot{m}_i$ (kg/s) is the mass flow, c_{pi} (kJ/kg K) the specific heat, T (K) and T_0 (K) are the mass flow temperatures and the reference environment temperature, respectively. M_i is the molecular weight of the mass flow i.

The term pressure on the right of the equation (5) is used to calculate entropy when the fluid is an ideal gas. This term is cancelled out for liquids and solids. In this study, for gases, the term pressure has not been used either, as all the gases involved in the firing process were assumed to be at atmospheric pressure ($p=p_0$).

The chemical exergy contained in the material flows was calculated using the equation:

$$\dot{A}_{q,i} = \frac{\dot{m}_i}{M_i} \cdot a_q \qquad (6)$$

Where $\dot{m}_i$ is the mass flow rate (kg/s), and a_q its specific chemical exergy. For a mixture of ideal gases, the specific chemical exergy a_q is given by the expression:

$$a_q = \sum_j \left(y_j \cdot a_{q,j}\right) + RT_0 \sum_j \left(y_j \cdot \ln\left(y_j\right)\right) \qquad (7)$$

Where y_j is the mole fraction of the chemical substance j and $a_{q,j}$ the value of its standard chemical exergy. Using this equation, it is possible to calculate the chemical exergy of gaseous fuels (Valero, A., 2008).

For gases, the reference substances used for calculating chemical exergy are the free gaseous components present in atmospheric air (O_2, N_2, Ar, He, Ne, Kr, Xe, H_2O and CO_2) and their standard chemical exergy results from their standard concentration in the atmosphere (Ferrer, S., 2016, Szargut, 1986 and 2005).

For solids, the calculation of chemical exergy follows the same procedure, but in this case, the solids appearing in the earth’s upper crust are used as reference substances (Valero, A., 2008).

The exergy change that accompanies a flow process with chemical reaction M + N → P is related to the Gibbs free energy of reaction ΔG^0, and can be calculated by the following equation (Ferrer, S., 2016):

$$\dot{A}_{q,M} + \dot{A}_{q,N} - \dot{A}_{q,P} = \Delta G^0 \qquad (8)$$

2.2. EXERGY OF A HEAT FLOW ($\dot{A}_Q$)

The exergy transfer that accompanies a heat flow ($\dot{A}_Q$), at a temperature T_f, may be obtained by the following expression (Moran and Shapiro, 2006):

$$\dot{A}_Q = \left(1 - \frac{T_0}{T_f}\right) \cdot \dot{Q}_f \qquad (9)$$

This term is associated with the heat exchange in the system during the process, and indicates the maximum work that may be carried out by a certain heat stream at temperature T_f using the environment, at temperature T_0, as a cold focus. This term is equivalent to the work carried out by a Carnot engine operating between two foci at temperatures T_f and T_0.

2.3. EXERGY DESTRUCTION ($\dot{A}_D$)

Finally, the term $\dot{A}_D$ represents exergy destruction per unit time due to the internal irreversibilities of the system and may be expressed as:

$$\dot{A}_D = T_0 \cdot \sigma \qquad (10)$$

The exergy destruction of a process is always $T_0 \cdot \sigma$. This is the Gouy-Stodola Theorem (Valero and Lozano, 1987), which establishes that exergy destruction is proportional to the product of the reference temperature (T_0) through the generation of entropy within the system (σ).

Exergy analysis allows identification and quantification of the irreversibilities of the process or sources of exergy destruction, which show how to improve the functioning of a system in order to enhance process energy efficiency.

3. OBJECTIVE

An exergy balance was carried out on a continuous single-layer roller kiln during the firing of porcelain tiles, in which the exergy of each of the streams involved in the process, as well as the corresponding exergy efficiency, was calculated. The application of this analysis method and the results obtained have allowed certain courses of action aimed at improving kiln efficiency to be addressed.

4. METHODOLOGY USED

In this section a description of the studied kiln is detailed, as well as the characteristics of the materials involved in the study.

4.1. DESCRIPTION OF THE STUDIED KILN

The studied kiln was a single-layer roller kiln, 112.71 metres long, consisting of 51 modules of 2.21 metres each. The product being manufactured during the study was porcelain stoneware tile.

Heat was supplied by natural gas combustion at the burners, in which air and gas were fed in through different inlets. The fumes generated by natural gas combustion at the burners were extracted from the kiln through the exhaust stack located at the kiln entrance. The exhaust stack contained an ambient air inlet to reduce flue gas temperature and to protect the fan. The firing area was separated from the cooling area by a firebreak. The cooling gases left the kiln through the cooling stack. figure 2 shows a diagram of the studied kiln.

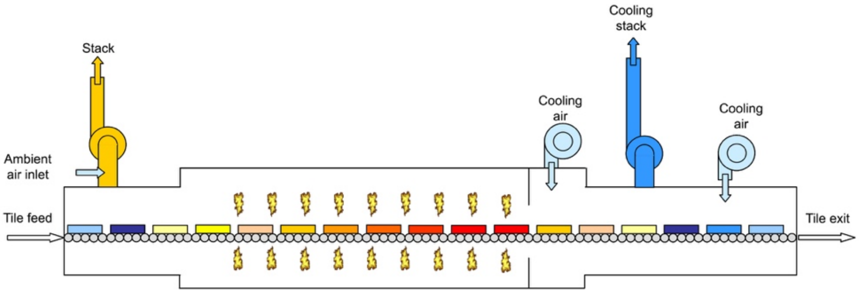

Figure 2. *Diagram of the single-layer roller kiln studied.*

To carry out the exergy balance on the industrial continuous roller kiln, thermodynamically, as a control volume (open system) and during the experimental measurements, the following assumptions were made:

a) a) The kiln operated in a steady state.

b) b) The changes in kinetic and potential energy in the inflows and outflows were negligible. In addition, electric energy consumption was not considered in the balance, given that this was very small compared to thermal energy consumption (Monfort et al., 2010).

c) c) Air, natural gas and combustion gases behaved as ideal gases.

d) d) The magnitude of the work performed inside the kiln, due to the movement of the material by the rollers, was so small as to be negligible.

To carry out the balance on a certain property in an industrial facility, in this case a kiln, it is necessary, first, to define the environment in which the balance is to be performed. All the flows entering or leaving the environment must then be identified. Finally, the variables are experimentally determined to calculate the amount of the targeted property in each stream.

A diagram of the environment selected to carry out the balance, as well as the streams involved in the process, is shown in figure 3.

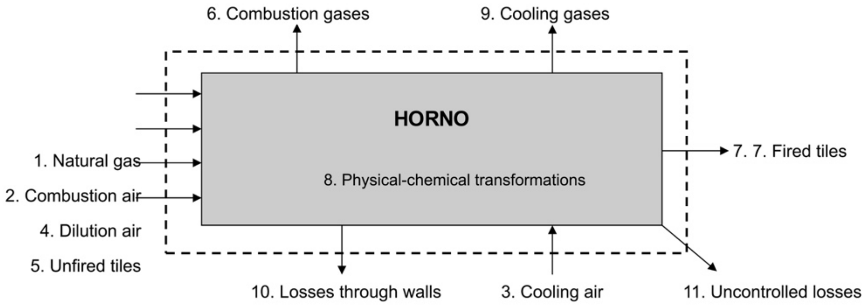

Figure 3. *Streams involved in the balance on the roller kiln studied, and balance environment.*

4.2. COMPOSITION OF THE NATURAL GAS FED INTO THE KILN

Although a natural gas composition may present slight variations over time, the composition considered during this study was that shown in table 1, which corresponds to the average composition of the natural gas distributed in Castellón province (Mallol et al., 2001).

Parameters		Value
Chemical composition (% by volume)	CH_4 (g)	90
	C_2H_6 (g)	7.5
	C_3H_8 (g)	1.5
	C_4H_{10} (g)	0.40
	N_2 (g)	0.60
	Sulphur in the odorizer	6.6 mg/m_n^3

Table 1. *Average composition of natural gas distributed in Castellón province.*

4.3. CHARACTERISTICS OF THE GASEOUS STREAMS EMITTED THROUGH THE STACKS: COMBUSTION AND COOLING GASES

The chemical composition of the combustion gases and of the cooling gases (which were basically air) released from the kiln into the outside air was determined experimentally (table 2) using a portable combustion gas analyzer (Kane 350 XL).

Parameters		**Combustion gases**	**Cooling gases**
Chemical composition (% by volume)	CO_2 (g)	2.64	---
	H_2O (g)	5.07	---
	O_2 (g)	15.30	21.00
	N_2 (g)	77.00	79.00
Temperature (K)		511.8	425.0

Table 2. *Combustion and cooling gas composition and temperature.*

4.4. CHARACTERISTICS OF THE PORCELAIN STONEWARE TILE COMPOSITION

The characteristics of the studied porcelain stoneware tile, as well as the chemical and mineralogical composition of both the unfired and fired tile body, were studied elsewhere (Ferrer, S. et al., 2015).

4.5. EXERGY BALANCE ON A CONTINUOUS ROLLER KILN

Particularizing equation (1) to the kiln inflow and outflow streams, the expression for the exergy balance may be written as follows:

$$\dot{A}_D = (\dot{A}_g + \dot{A}_{ac} + \dot{A}_{ae} + \dot{A}_{ad} + \dot{A}_{cr}) - (\dot{A}_{gc} + \dot{A}_r + \dot{A}_{cc} + \dot{A}_{ge}) + \dot{A}_{Qp} + \dot{A}_{Qi} \qquad (11)$$

where the exergy balance on the kiln, expressed as a function of exergy destruction, includes the exergy flows at the kiln entrance, which were: fuel ($\dot{A}_g$), combustion air ($\dot{A}_{ac}$), air used for tile cooling ($\dot{A}_{ae}$), entry of unfired tiles ($\dot{A}_{cr}$) and air used in diluting combustion gases ($\dot{A}_{ad}$), before exiting through the exhaust stack.

The kiln outflows correspond to the combustion gases ($\dot{A}_{gc}$), cooling gases ($\dot{A}_{ge}$), fired tiles ($\dot{A}_{cc}$) and their reaction exergy ($\dot{A}_r$), heat exergy losses through kiln surfaces kiln ($\dot{A}_{Qp}$) and uncontrolled losses ($\dot{A}_{Qi}$). The environment, as well as the streams involved in the analysis, is shown in figure 3.

The exergy of the air streams $\dot{A}_{ac}$, $\dot{A}_{ae}$, $\dot{A}_{ad}$, and that of the cooling gases $\dot{A}_{ge}$ were calculated by means of equation (3), from thermodynamic tables (Çengel and Boles, 2006).

The physical exergy of the natural gas ($\dot{A}_{f,g}$) and the physical exergy of the unfired and fired ceramic composition ($\dot{A}_{f,cr}$ and $\dot{A}_{f,cc}$) were calculated from equations (4) and (5).

Heat exergy losses through kiln surfaces ($\dot{A}_{Qp}$), and uncontrolled losses ($\dot{A}_{Qi}$) were calculated by equation (9).

The chemical exergy provided by natural gas combustion ($\dot{A}_{q,g}$) was calculated by the expression:

$$\dot{A}_{q,g} = \dot{m}_g \cdot a_{q,g} \tag{12}$$

where $a_{q,g}$ is the specific chemical exergy of natural gas, determined from its composition (table 1) applying equation (7), and its value was 14.10 kWh/kg natural gas.

To determine the physical component of the combustion gases ($\dot{A}_{f,gc}$), equation (3), was used, while for the calculation of its chemical exergy ($\dot{A}_{q,gc}$), equation(7) was used. For both calculations it was necessary to know their composition (table 2).

The chemical exergy consumed in the physical-chemical transformations that took place during heat treatment of the porcelain tiles ($\dot{A}_r$) was calculated by equation (8), according to the reactions proposed by Ferrer et al., 2015.

The standard chemical exergy values used in the calculations were obtained from Szargut, 1986 and 2005 and Kotas, 1996.

Kiln exergy efficiency was defined by considering useful exergy to be the cumulative chemical exergy in the product, in this case the chemical exergy necessary to carry out the physical-chemical transformations that took place during firing of the porcelain stoneware tile composition ($\dot{A}_r$). Therefore, kiln exergy efficiency may be expressed as:

$$\eta_{\dot{A}}(\%)=\frac{\dot{A}_r}{\dot{A}}\cdot 100 \tag{13}$$

Where $\dot{A}$ is the total exergy supplied to the kiln.

5. RESULTS OBTAINED

The results obtained after calculating the exergy of each of the streams involved in the firing process and their contribution (percentage) to the exergy balance are shown in table 3. The number in parentheses indicates the reference given in figure 3 for each flow involved in the balance.

EXERGY	Stream	Stream exergy symbol	Physical exergy (kW)	Chemical exergy (kW)	Total exergy (kW)	Contrib. (%)
INPUT EXERGY	(1) Natural gas	$\dot{A}_g$	---	4,668.85	4,668.85	87.30
	(2) Combustion air	$\dot{A}_{ac}$	0.26	---	0.26	0.00
	(3) Cooling air	$\dot{A}_{ae}$	1.60	---	1.60	0.03
	(4) Ambient air dilution	$\dot{A}_{ad}$	0.34	---	0.34	0.01
	(5) Unfired tiles	$\dot{A}_{cr}$	0.19	676.63	676.82	12.66
	TOTAL	---	**2.39**	**5,345.48**	**5,347.88**	**100**
OUTPUT EXERGY	(6) Combustion gases	$\dot{A}_{gc}$	290.73	79.98	370.71	6.93
	(7) Fired tiles	$\dot{A}_{cc}$	18.31	710.36	728.67	13.63
	(9) Cooling gases	$\dot{A}_{ge}$	286.22	---	286.22	5.35
	(10) Losses through walls	$-\dot{A}_{Qp}$	49.64	---	49.64	0.93
	(11) Uncontrolled losses	$-\dot{A}_{Qi}$	62.87	---	62.87	1.18
	TOTAL	---	**707.77**	**790.34**	**1,498.11**	**28.01**
USEFUL EXERGY	(8) Physical - chemical transformations	$\dot{A}_r$	---	**455.99**	**455.99**	**8.53**
EXERGY DESTRUCTION	TOTAL	$\dot{A}_D$	**---**	**---**	**3,393.44**	**63.46**

Table 3. *Results obtained in the exergy balance on the kiln.*

According to the data shown in table 3, from the exergy balance it may be concluded that:

- The main source of exergy in the kiln was natural gas combustion (4669 kW). Part of this exergy was used to carry out the physical-chemical transformations of the material, the main objective of the firing operation. Specifically, in the kiln studied, the useful exergy used in the physical-chemical transformations of the material during the firing process was 8.53%.
- Most of the exergy contributed to the kiln was destroyed because of the irreversibilities present in the kiln. The rest was dissipated in combustion and cooling gas flows, as well as in heat losses to the environment.
- The irreversibilities present in the system caused the exergy destruction for the entire kiln to be 3393 kW (63.46%). Dividing the kiln into several subsystems, allowed more detailed analysis and identification of the subsystems where exergy destruction occurred. The results are detailed in table 4, in which only the destroyed physical exergy has been calculated.

Subsystems	Exergy destruction (kW)	Percentage (%)
Ceramic material processed	1,001	30
Combustion reaction	925	27
Heat losses through walls and losses throughout the entire kiln	829	24
Heat exchange process during tile cooling	654	19
TOTAL	**3,420**	**100**

Table 4. *Location of kiln irreversibilities.*

The exergy efficiency of the kiln amounted to 8.53%. It should be noted that the destroyed exergy could not be recovered, but the exergy remaining in the form of residual heat was potentially recoverable (at least partially) in secondary facilities or in the kiln itself. Therefore, it would be of great interest to determine this value in order to implement possible improvements in the system. Consequently, if the remaining exergy were used, the potential exergy output of the kiln could amount to 36.54%.

- **Example of analysis of the influence of operating conditions on energy and exergy**

One of the minimizable irreversibilities identified in the kiln was tile cooling. In this case it would be possible *to operate on the cooling air flow rate*, which largely depended on kiln operating conditions.

The specific air flow rate used for cooling depended on kiln design (length of the cooling zone, air-tile contact system, etc.), which indicates that it is possible to operate at different specific flow rates (kg air/kg processed product).

The way in which the exergy contained in the kiln cooling gases would vary according to the air-product ratio introduced for the cooling of the fired material is shown in figure 4. For this, the enthalpy of the cooling gas stream was assumed to remain constant (1701 kW), and the gas temperature was recalculated when tiles were cooled with different air-fired product mass ratios.

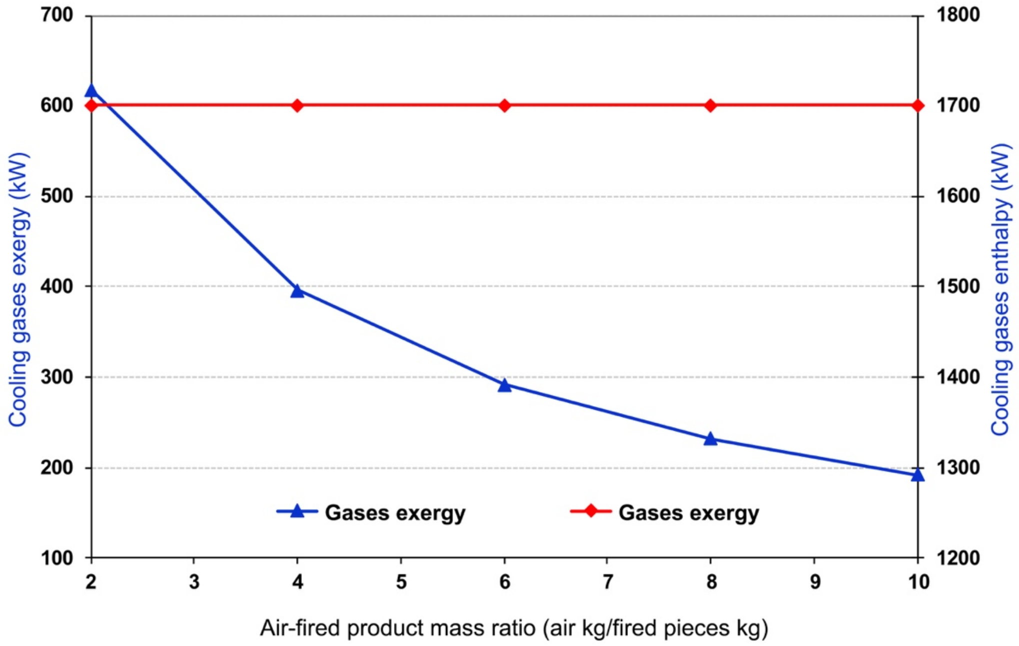

Figure 4. *Variation of cooling gas exergy according to the specific cooling air flow rate, keeping output stream energy constant.*

The results obtained indicate that the exergy destroyed during cooling could be reduced by introducing less air to cool the material. This could be achieved by optimizing air-tile contact as much as possible, so that, with a smaller amount of air, tile temperature was reduced more effectively. In addition, the exergy contained in the cooling gases would increase significantly because the stream would have a lower air mass flow rate, but higher temperature. Therefore, this would increase its quality and facilitate subsequent use, for example, in a heat recovery system.

6. CONCLUSIONS

The study shows that the efficiency of the single-layer roller kiln was mainly affected by the exergy destroyed during natural gas combustion, in heat transfer and in combustion and cooling gases.

The experimental measurements indicate that these factors accounted for more than 63% of the total exergy supplied to the kiln. This means that 63% of the exergy was destroyed or lost in a non-useful way during the firing process.

To increase kiln exergy efficiency, some of the operating parameters need to be controlled. These include: excess combustion air, the specific air flow rate used to cool the ceramic material, implementation of certain actions such as preheating combustion air or installation of recovery systems.

The results suggest that the reduction of exergy losses during cooling is a very important issue for the improvement of kiln exergy performance (if the remaining exergy is subsequently used).

Identification of avoidable and unavoidable exergy destruction sources, as well as avoidable exergy losses in the process, will facilitate selection of the most suitable set of actions to increase kiln efficiency.

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