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Tittle: Energy Analysis of a Ceramic Kiln

Author

Sergio Domínguez García

Director

Kamil Śmierciew

Bialystok University of Technology
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Escuela de
Ingeniería y Arquitectura
Universidad Zaragoza

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Energy analysis of a ceramic kiln

Summary

This project consists in the analysis of a ceramic kiln, analysing the process of combustion occurred as well as the analysis of what happened in terms of energy. Chemistry has been used in the case of combustion and various thermodynamic principles in the energy analysis. Furthermore, in the analysis also has to take into account the performance of the furnace as well as the quantity of gases that take place in the combustion.

In addition, since there are energy losses in the furnace and it is not possible to take advantage of all the energy of the fuel, the possibility of saving energy by means of some system has been studied. In this case it has been chosen to take advantage of the energy contained in the combustion gases, by means of a design of an air preheater to heat the air used in the combustion. In the design of the heat exchanger, knowledge has been used in the area of heat transfer and in the area of fluid mechanics.

Moreover, an important aspect of the work has been the analysis of the savings of the installation of this preheater, in terms of energy as in terms of money.

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1. Introduction

The requirements of the global market for energy economy and environmental control have been growing in recent years, and as a consequence the industry faces new challenges to adjust itself to the reality of this niche. This adjustment includes a complete rearrangement of the production processes of companies, from the preparation of the raw material to the delivery of products, with the adoption of new technologies and updating of existing equipment.

In the case of ceramic components, manufacture takes place as follows:

1. The raw material is clay. Use of water, silica, lead, tin and metal oxides (depending on the type of ceramic).
2. They are grinded to a very fine powder or mixed in the most suitable proportion.
3. The powder is introduced into the mold that will form the piece.
4. Some things are to the static press, but up to 3000 kg/cm^2.
5. Bake at a temperature of 1600 and 2000 degrees Celsius. The process of pressing and firing is called sintering.

However the pieces do not come out absolutely perfect from the press and some of the things will impose a later calibration adjustment. The enormous hardness of the material now becomes an inconvenience, since only the diamond can be used in its carving. Even with this type of tools remodeling is slow and laborious and wear quickly, which greatly increases costs. As an alternative, new methods of treatment of ceramic surfaces based on ultrasound are being investigated.

For this process of making ceramics, it is necessary to cook the piece at very high temperatures, so that a device capable of reaching these temperatures is necessary. Ovens are used, which need an energy supply, either electric or a fuel and therefore also appears a combustion process, in which energy is released, necessary for the process of cooking the piece can be carried out.

By burning this fuel, combustion gases are released into the atmosphere. It is necessary to control them, both their composition as well as the temperature at which they are expelled. This control is necessary to maintain an environmental commitment and try to contaminate as little as possible, strictly complying with the laws and thus conserve the planet for future generations.

2. Kiln

A kiln is a thermally insulated chamber, a type of oven, that produces temperatures sufficient to complete some process, such as hardening, drying, or chemical changes. Kilns have been used for millennia to turn objects made from clay into pottery, tiles and bricks. Various industries use rotary kilns for pyroprocessing—to calcinate ores, to calcinate limestone to lime for cement, and to transform many other materials.

Kilns are an essential part of the manufacture of all ceramics. Ceramics require heat at high temperatures so chemical and physical reactions will occur to permanently alter the unfired body. In the case of pottery, clay materials are shaped, dried and then fired in a kiln. The final characteristics are determined by the composition and preparation of the clay body, by the temperature at which it is fired. After a first firing glazes may be used and the ware is fired a second time to fuse the glaze into the body. A third firing at a lower temperature may be required to fix overglaze decoration. Modern kilns often have sophisticated electrical control systems to firing regime, although pyrometric devices are often also used.

Clay consists of fine-grained particles, that are relatively weak and porous. Clay is combined with other minerals to create a workable clay body. Part of the firing process includes sintering. This heats the clay until the particles partially melt and flow together, creating a strong, single mass, composed of a glassy phase interspersed with pores and crystalline material. Through firing, the pores are reduced in size, causing the material to shrink slightly. This crystalline material predominantly consists of silicon and aluminium oxides.

Types of modern commercial kiln

In the broadest terms, there are two types of kiln: intermittent and continuous, both sharing the same basic characteristics of being an insulated box with a controlled inner temperature and atmosphere.

A continuous kiln, sometimes called a tunnel kiln, is a long structure in which only the central portion is directly heated. From the cool entrance, ware is slowly transported through the kiln, and its temperature is increased steadily as it approaches the central, hottest part of the kiln. From there, it continues through the kiln, and the surrounding temperature is reduced until it exits the kiln nearly at room temperature. A continuous kiln is energy-efficient, because heat given off during cooling is recycled to pre-heat the incoming ware. In some designs, the ware is left in one place, while the heating zone moves across it.

In the intermittent kiln. the ware to be fired is placed into the kiln. The kiln is closed, and the internal temperature increased according to a schedule. After the firing is completed, both the kiln and the ware are cooled. The ware is removed, the kiln is cleaned and the next cycle begins.

In normal conditions it generates approximately 4500 kW with which all the needs of the installation are covered and there is a small surplus of gases that will be emitted to the atmosphere, after passage through the filters of the multicyclones, minimizing the environmental impact.

In the following page there ir some pictures than describes the kiln, figures 1 and 2.

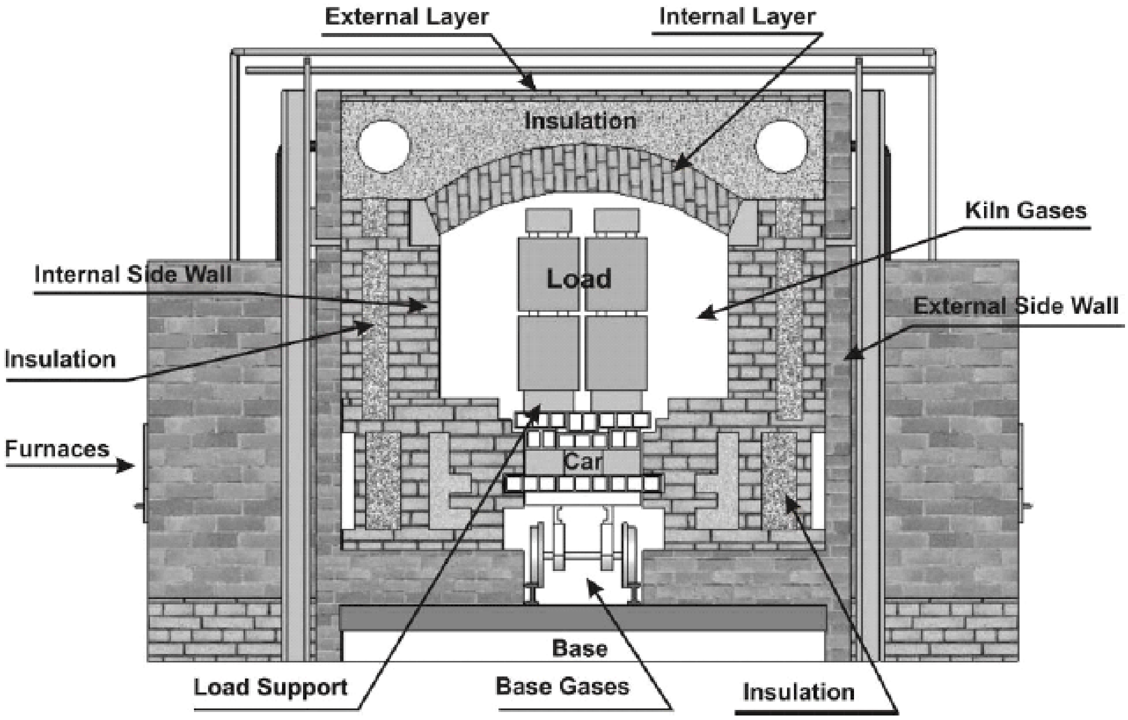


Figure 1. Ceramic kiln

The operating diagram of the oven is shown in the figure below. As you can see the bricks are introduced into the oven for drying for later use.

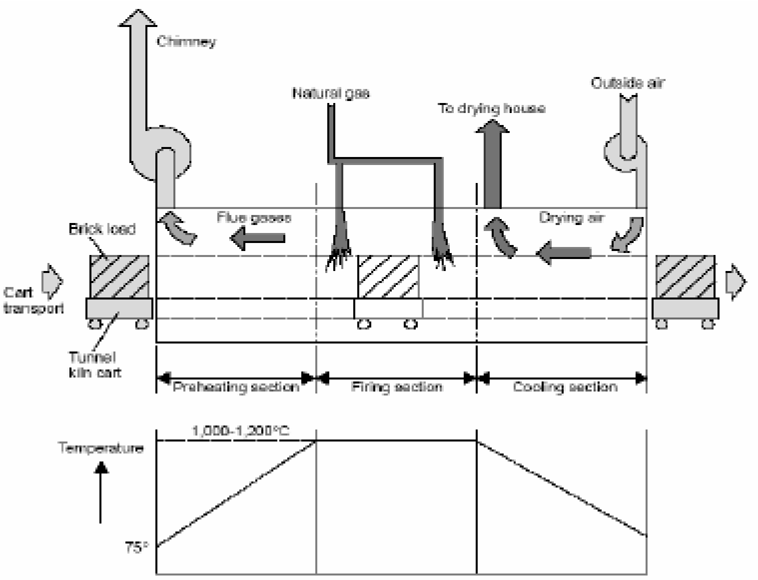


Figure 2. Schematic diagram of a tunnel kiln

3. Combustion. Mass Balance

By combustion is understood the rapid reaction of oxygen that takes place between a fuel and oxygen of the air, releasing a great amount of heat. The fuels are formed mainly by Carbon, Hydrogen, Oxygen, Sulfur and traces of other elements. The air, besides oxygen, has significant amounts of nitrogen (79%), which has no active role in the combustion, at the very least a small part can react with oxygen giving rise to oxides of nitrogen, reaction that does not involve any contribution energetic.

The combustion is complete when all products resulting from the reaction are at the highest possible degree of oxidation. The required theoretical amount of air for the reaction to be complete is called stoichiometric air and the combustion is called complete or stoichiometric.

In fact, we only supply the theoretical air necessary if there are incomplete reactions. In this type of reactions would not get to have the products in their maximum degree of oxidation. You would not get the maximum energy available in the fuel. These products are completely oxidized and are called carbon monoxide, carbon and hydrocarbons.

It is therefore necessary to provide an excess of air in order to exploit the full potential of the fuel. The relation of the air actually used on the theoretical is called excess of air.

The stoichiometric or excess combustion processes can be determined from the elemental composition of the fuel, which provides the weights of each component of fuel: C, H, O, N, S, ash and water, expressed in Kmol component / Kmol of fuel.

The products that will be obtained are through the development of the reactions of the components of the fuel with the oxygen of the air.

In the case of this kiln, the used fuel is natural gas, which has the following volumetric composition:

- $CH_4 = 0{,}926$
- $C_2H_6 = 0{,}036$
- $C_3H_8 = 0{,}008$
- $C_4H_{10} = 0{,}003$
- $N_2 = 0{,}027$

In the combustion process of a fuel, said fuel is mixed with air giving rise to elements.

$$C_nH_m + Air \rightarrow CO_2 + H_2O + N_2 + O_2 + CO \qquad \textit{eq. 1}$$

The air of our environment has a volumetric composition:

- $O_2 = 20{,}95$
- $N_2 = 79{,}05$

The amount of nitrogen per unit of oxygen is $79{,}05/20{,}95 = 3{,}77$.

The reaction produced in the combustion process using natural gas as fuel and considering complete and excess air combustion

$$Fuel + a'(O_2 + 3{,}77 \cdot N_2) \rightarrow b \cdot CO_2 + c \cdot H_2O + d'N_2 + e' \cdot O_2 \qquad \textit{eq. 2}$$

To adjust the above reaction, the matter balances are applied to each element under stoichiometric conditions, taking into account that in these conditions there is no excess air and the combustion is complete:

$$\mathrm{Fuel} + \mathrm{a}(\mathrm{O_2} + 3{,}77 \cdot \mathrm{N_2}) \rightarrow \mathrm{b} \cdot \mathrm{CO_2} + \mathrm{c} \cdot \mathrm{H_2O} + \mathrm{d} \cdot \mathrm{N_2} \qquad \textit{eq. 3}$$

C balance: $0{,}926 \cdot 1 + 0{,}036 \cdot 2 + 0{,}008 \cdot 3 + 0{,}003 \cdot 4 = b$

H balance: $0{,}926 \cdot 4 + 0{,}036 \cdot 6 + 0{,}008 \cdot 8 + 0{,}003 \cdot 10 = 2 \cdot c$

O balance: $2 \cdot a = 2 \cdot b + c$

N balance: $2 \cdot 0{,}027 + 2 \cdot a \cdot 3{,}77 = 2 \cdot d$

For combustion to occur properly in the kiln, the air is introduced in excess, being that of 25 %. It is also considered that the combustion is complete, so there is no CO in the exhaust gases.

Taking into account the previous premises, the reaction changes and also the coefficients:

$$\mathrm{Fuel} + \mathrm{a}'(\mathrm{O_2} + 3{,}77 \cdot \mathrm{N_2}) \rightarrow \mathrm{b} \cdot \mathrm{CO_2} + \mathrm{c} \cdot \mathrm{H_2O} + \mathrm{d}'\mathrm{N_2} + \mathrm{e}' \cdot \mathrm{O_2} \qquad \textit{eq. 4}$$

O balance: $2 \cdot a' = 2 \cdot b + c + 2 \cdot e'$

N balance: $2 \cdot 0{,}027 + 2 \cdot a' \cdot 3{,}77 = 2 \cdot d'$

Excess air: $a' = a \cdot (1 + 0{,}25)$

With all of the above equations, eq. 1, 2, 3, 4, the mass balance is solved, represented in the table 1. That table represents the quantity of reagents and products that are obtained from 1 kmol of fuel.

Mass balance in the combustion per 1 kmol of fuel					
AIR	(kmol)	FUEL	(kmol)	GASES	(kmol)
N_2	9,602	CH_4	0,926	CO_2	1,034
O_2	2,547	C_2H_6	0,036	H_2O	2,007
		C_3H_8	0,008	N_2	9,637
		C_4H_{10}	0,003	O_2	0,5094
		N_2	0,027	CO	0

Table 1.Mass balance in the combustion per 1 kmol of fuel

4. Energy analysis in the kiln. Calculations of energy balance

After knowing the volumetric composition of the exhaust gases and the amount of air necessary for combustion, the next step in the energy analysis of the furnace is to know the amount of fuel needed to achieve the required power, which in the case of manufacture of ceramic stoneware is 4500 kW. To do this, it is necessary to apply an energy balance to the entrance and exit of the oven, using the first law of thermodynamics, eq. 5.

$$\dot{E}_{fuel} + \dot{E}_{air} = \dot{Q}_{useful} + \dot{E}_{gases}$$

eq. 5

In this case, being a gaseous fuel (natural gas), there is no solid waste as a by-product of combustion as would occur in the combustion of a solid (coal or biomass) which has ash and part of the unreacted carbon. Furthermore, the air inlet temperature is considered to be 25°C and the outlet temperature of the gases is approximately 400°C.

$$\dot{E}_{fuel} = \dot{n}_{fuel} \cdot \left(\sum kmol_{fuel,i} \cdot h_{fuel,i}\left(T_{fuel,i}\right)\right)$$

eq. 6

$$\dot{E}_{air} = \dot{n}_{fuel} \cdot \left(kmol_{O_2} \cdot h_{O_2}\left(T_{e,air}\right) + kmol_{N_2} \cdot h_{N_2}\left(T_{e,air}\right)\right)$$

eq. 7

$$\dot{E}_{gases} = \dot{n}_{fuel} \cdot \left(\sum kmol_{gases,i} \cdot h_{gases,i}\left(T_{out_{gases,i}}\right)\right)$$

eq. 8

All the enthalpies are known, so with the above equations, eq. 5, 6, 7, 8, the molar flow rate of fuel is known: $\dot{n}_{fuel} = 0{,}006795\ \mathrm{kmol/s}$.

To obtain the fuel consumption per hour under normal conditions: $(\mathrm{T_n} = 25\ ℃; \mathrm{P_n} = 1\ \mathrm{atm})$

$$\dot{V}_{fuel_{hour}} = \frac{\dot{n} \cdot R \cdot T_n}{P_n} \cdot 3600 = 548{,}2\ m^3/hour$$

eq. 9

In the event that the company works 800 hours a year, the annual consumption will be:

$$\dot{V}_{fuel_{year}} = \dot{V}_{fuel_{hour}} \cdot 8000 = 4{,}386 \cdot 10^6 m^3/year$$

eq. 10

Another way of representing the capacity of a fuel is by the heating value. It is the heat released by burning 1 kmol of fuel under a series of conditions:

- Complete and stoichiometric combustion
- Using dry air as oxidizer
- The fuel and the air enter at the thermodynamic reference temperature, at 25°C
- Cooling the combustion products to the thermodynamic reference temperature 25°C

There are two types of heating value: higher (HHV) and lower (LHV).

In the higher heating value, the water that leave the system does it in state of saturated liquid at the reference temperature.

$$E_{fuel}(25℃) + E_{dry_{air}}(25℃) = HHV + E_{dry_{gases}}(25℃) + E_{\mathrm{H_2O}}(25℃)$$

eq. 11

$$E_{fuel}(25℃) = \sum kmol_{fuel,i} \cdot h_{fuel,i}(25℃)$$

eq. 12

$$E_{dry_{air}}(25℃) = kmol_{O_2} \cdot h_{O_2}(25℃) + kmol_{N_2} \cdot h_{N_2}(25℃)$$

eq. 13

$$E_{dry_{gases}}(25℃) = \sum kmol_{gases,i} \cdot h_{gases,i}(25℃)$$

eq. 14

$$E_{\mathrm{H_2O}}(25°\mathrm{C}) = kmol_{\mathrm{H_2O}} \cdot \left(h_{\mathrm{H_2O}}(25°\mathrm{C}) + h_{latentHeat_{\mathrm{H_2O}}}(25°\mathrm{C})\right) \qquad \textbf{eq. 15}$$

To calculate the enthalpy of water in a saturated liquid state, the enthalpy of the water is approximated at 25°C and the latent heat of vaporization is added at the same temperature.

Solving the above equation, eq. 11, it's possible to calculate the higher heating value: $\mathrm{HHV} = 907148\ \mathrm{kJ}$.

In the lower heating value, the water that leave the system does it in state of saturated vapour at the reference temperature.

$$E_{fuel}(25°\mathrm{C}) + E_{dry_{air}}(25°\mathrm{C}) = LHV + E_{dry_{gases}}(25°\mathrm{C}) + E_{\mathrm{H_2O}}(25°\mathrm{C}) \qquad \textbf{eq. 16}$$

$$E_{fuel}(25°\mathrm{C}) = \sum kmol_{fuel,i} \cdot h_{fuel,i}(25°\mathrm{C}) \qquad \textbf{eq. 17}$$

$$E_{dry_{air}}(25°\mathrm{C}) = kmol_{O_2} \cdot h_{O_2}(25°\mathrm{C}) + kmol_{N_2} \cdot h_{N_2}(25°\mathrm{C}) \qquad \textbf{eq. 18}$$

$$E_{dry_{gases}}(25°\mathrm{C}) = \sum kmol_{gases,i} \cdot h_{gases,i}(25°\mathrm{C}) \qquad \textbf{eq. 19}$$

$$E_{\mathrm{H_2O}}(25°\mathrm{C}) = kmol_{\mathrm{H_2O}} \cdot h_{\mathrm{H_2O}}(25°\mathrm{C}) \qquad \textbf{eq. 20}$$

Solving this equation, eq. 16, it's possible to calculate the higher heating value: $LHV = 818871\ kJ$.

One of the most important characteristics to analyse is the performance of the furnace, which shows the level of utilization of the primary energy of the fuel in useful energy.

$$\eta_{HHV} = \frac{\dot{Q}_{useful}}{\dot{n} \cdot HHV} \cdot 100 = 73{,}01\% \qquad \textbf{eq. 21}$$

$$\eta_{LHV} = \frac{\dot{Q}_{useful}}{\dot{n} \cdot LHV} \cdot 100 = 80{,}88\% \qquad \textbf{eq. 22}$$

If we analyse the value of the performance of the higher heating value, we can see that the 73% of the calorific power of the fuel is take into useful power. Since the furnace needs a power of 4500 kW, it will be necessary to introduce to the system approximately 6200 kW of higher heating value.

In the following page there is some graph, figure 3, representing this percentage of loses. The losses are mostly caused by the high temperature at which the gases emerge into the environment but are also due to heat losses in the kiln.

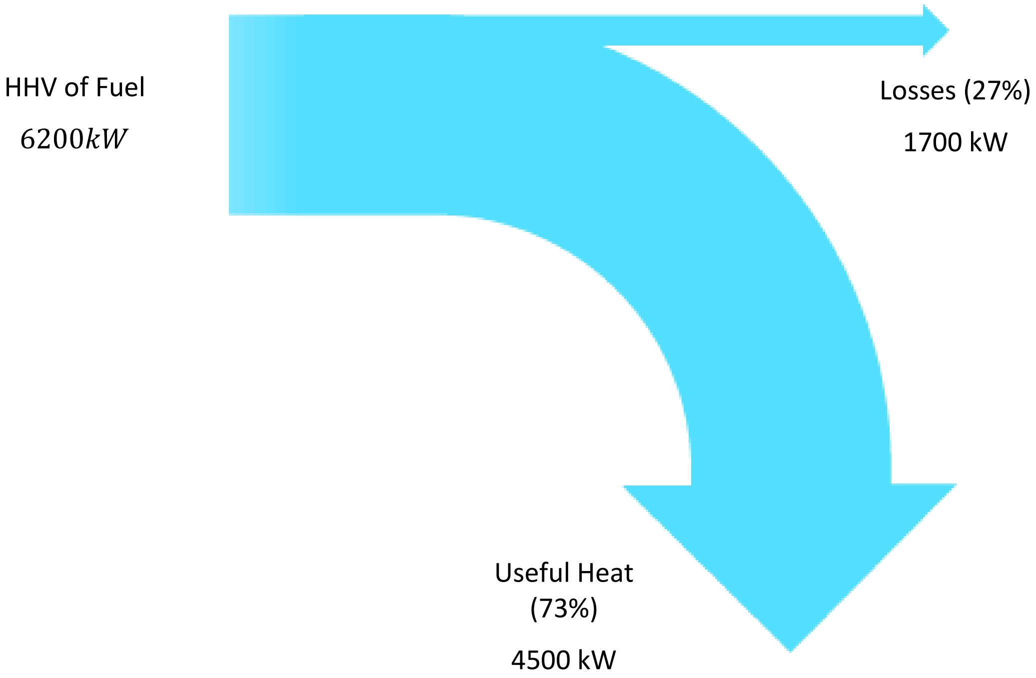


Figure 3. Energy consumption scheme

5. Calculations of energy saving by an air preheater

5.1. Introduction

Much energy escapes to the environment without taking advantage, reason why it is necessary to find a way to be able to use it and save fuel. Since most of the heat lost is due to the high temperature of the exhaust gases, we will study the possibility of using them in some way to recover part of the energy lost. A good way to recover the heat from the exhaust gas would be to give up part of its energy to the air used in the combustion.

In order to save energy different possibilities are being studying by using the energy of the exhaust gases. The recovery of the sensible heat of the gases at the exit of the boilers is carried out fundamentally and principally by means of heaters and air heaters. In this case, because we are not talking about a boiler but a kiln, in which there is no oil circuit to be able to use an economizer, we opt for the installation of an air preheater to increase the temperature of the air of the combustion.

When air heaters are used, the following effects occur:

- Heat losses in combustion gases are reduced. Approximately for each 20ºC of reduction of temperature of those gases obtains a 1% of saving of fuel.
- The flame temperature of the combustion zone is increased
- Excess air is reduced.

The mission of the air preheater is to increase the temperature of the combustion air by the energy of the exhaust gases, they are equipment that recover part of the sensible heat of the combustion gases and transfer it to the air required for the combustion of the fuel. It also allows control over the temperature of gases leaving the stack. Heaters are classified according to their operating principle:

- Tubular: the heat is transferred to the air from the same gases of the boiler as we can see in the figure 4.

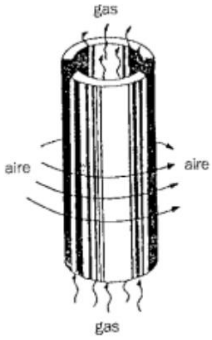


Figure 4. Tubular heater scheme of the heat

- Regenerative: the heat is transferred indirectly from the hot gases to the air through some means of heat storage. They are rotary or fixed as we can see in the figure 5.

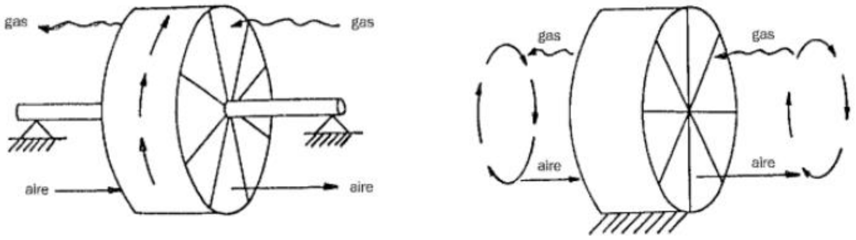


Figure 5. Regenerative heater scheme of the heat

Tubular heater

In this type of heater the flow of hot gases continuously passes through the inside or outside of the tubes, while the cooling air (oxidizer) circulates through the exterior or interior thereof as we can see in the figure 6.

The tubes used for their manufacture are generally 1 ½ ", 2" or 2 ½ "in diameter, low alloy in the cold end and carbon steel in the hot part.

The latest designs of air heaters of this type have arrangements for one or multiple air passages and are often divided into sections to reduce the length of the tubes.

Design Features:

- Air leaks or gases: they do not exist unless corrosion pores appear.
- Thermal expansion. It is relieved by allowing one end of the tubes to move independently of the tubular plate or one of the tubular plates to move independently of the heater housing.
- Corrosion. Low alloy pipes in the cold part and carbon steel pipes in the hot part.
- Pipe plugging. To avoid this, steam blowers and water cleaning are used.

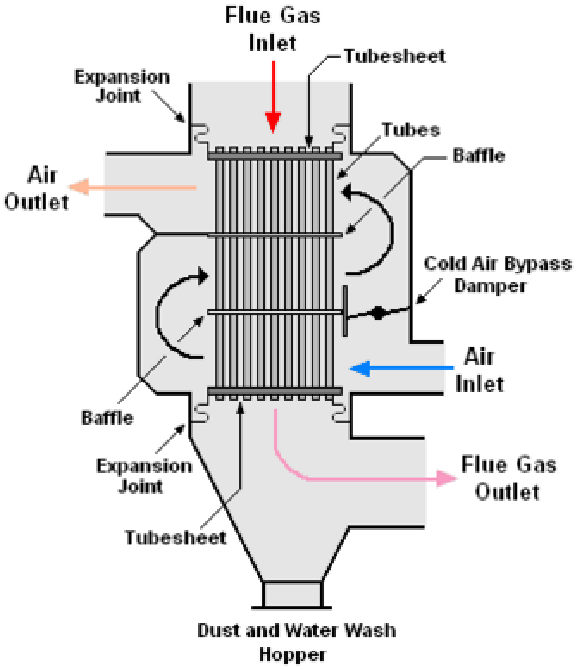


Figure 6. Example of a tubular heater scheme

Regenerative heater

They are characterized in that the heating surface is alternately subjected to the hot gas flow and the combustion air stream as we can see in the figure 7.

They may be:

- Rotating heating surface
- Fixed heating surface

The arrangement of the former is a function of whether they are horizontal or vertical axis of turbulent or laminar flow heating surface.

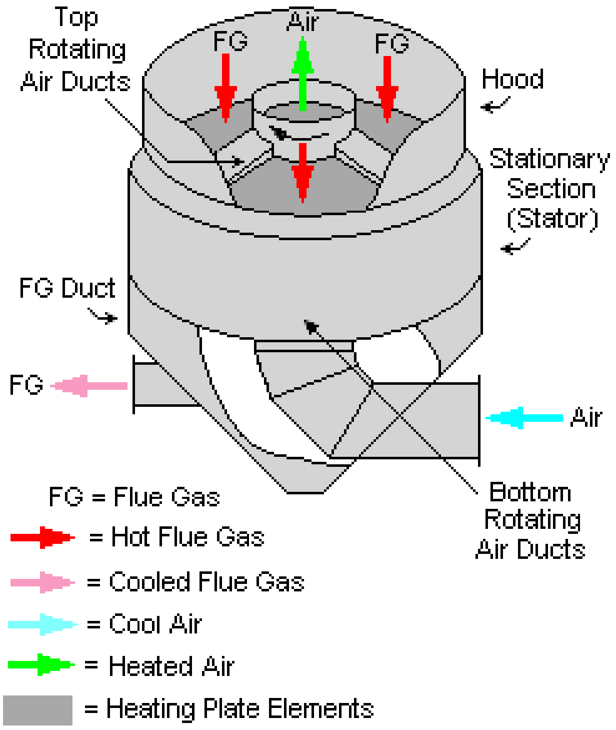


Figure 7. Example of a regenerative heater scheme

5.2. Design of a tubular preheater

We opt for the installation of a tubular preheater in the entrance of the chimney, figure 8.

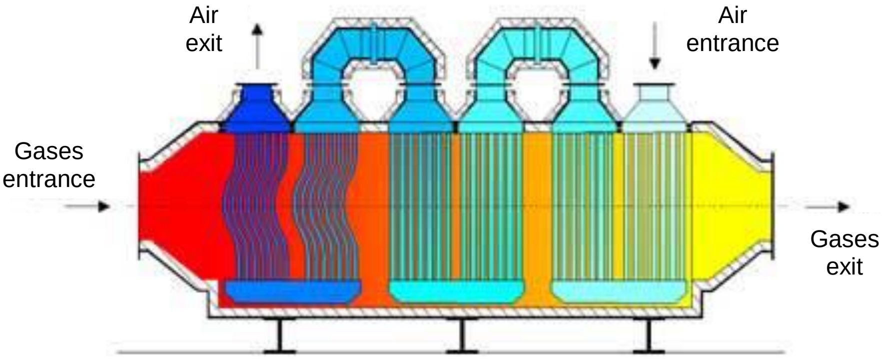


Figure 8. Example of a tubular preheater

The air preheater has the same design of the previous figure and in the next steps we will design it.

First of all is necessary to know the maximum temperature at which air can be heated. The exhaust gases cannot be cooled to less than 120℃ because it may lead acid condensations in preheater tubes. To determine that temperature of the air, is necessary to apply the energy balance in the preheater:

$$\dot{Q}_{pre} = \dot{n}_{fuel} \cdot \left(\sum kmol_{gases,i} \cdot C_{p_{gases,i}}\left(T_{m_g}\right)\right) \cdot \left(T_{ent_g} - T_{out_g}\right) \qquad \textbf{eq. 23}$$

$$\dot{Q}_{pre} = \dot{n}_{fuel} \cdot \left(kmol_{O_2} + kmol_{N_2}\right) \cdot C_{p_{gases,i}}\left(T_{m_{air}}\right) \cdot \left(T_{out_{air}} - T_{ent_{air}}\right) \qquad \textbf{eq. 24}$$

As we can see in the previous equation, the ideal gas approach is being done, and also, since the temperature of the air and the gases changes, the specific heat is evaluated at the average temperature.

Once solved, the heat exchanged in the heater is $802{,}7\ kW$; and the outlet air temperature is $351{,}3$ ℃.

As we can see, the maximum heat of the gases that can be used is $802{,}7\ kW$.

The design of the preheater tubes is similar to the one shown in the figure 9.

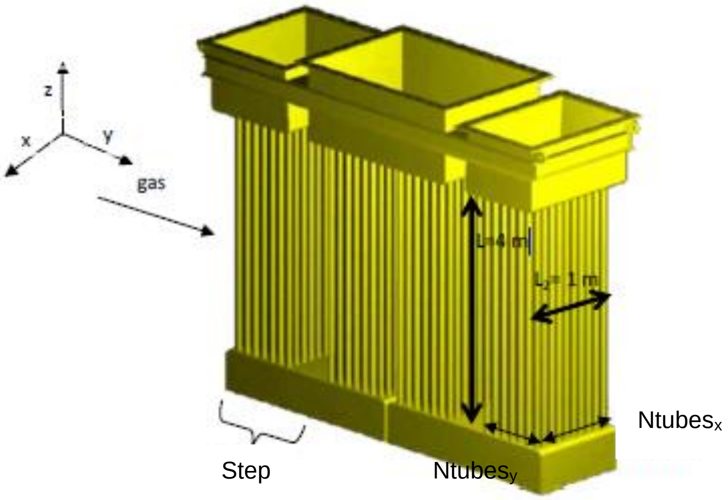


Figure 9. Example of the tubes in an air preheater

In this case the exhaust gases circulate on the outside of the tubes, while the air circulates in the interior. The dimensions of the preheater are the following:

- $L_z = 2\ m.$
- $L_x = 0{,}5\ m.$
- The air velocity inside the tubes must be about $v_{air} = 10\ m/s.$
- The tubes are considered commercial with a nominal diameter of $25{,}4\ mm$ and a thickness of $t = 1\ mm.\ (D_{tube} = D_{nom} + 2 \cdot t)$
- They tubes are made with carbon steel which conductivity is $K_{tube} = 40\ W/m \cdot K.$
- The arrangement of the tubes is aligned with a separation distance of twice the diameter in the two directions of the plane $S_x = S_y = 2 \cdot D_{tube}.$

Before starting the transfer of heat in the heat exchanger, it is necessary to know the number of tubes it contains in both directions. In the x direction:

$$L_x = N_x \cdot D_{tube} + (N_x - 1) \cdot (S_x - D_{tube}) \qquad \textbf{eq. 25}$$

And in the y direction is necessary to use the volumetric flow:

$$\dot{n}_{air} = \dot{n}_{fuel} \cdot \left(kmol_{O_2} + kmol_{N_2}\right) \qquad \textbf{eq. 26}$$

$$\dot{V}_{air} = \frac{\dot{n}_{air}}{\rho_{air}} \qquad \textbf{eq. 27}$$

$$\dot{V}_{air} = v_{air} \cdot \pi \cdot \frac{{D_{nom}}^2}{4} \cdot N_x \cdot N_y \qquad \textbf{eq. 28}$$

$$N_{tubes_{1step}} = N_x \cdot N_y \qquad \textbf{eq. 29}$$

Solving the previous equation, we can obtain the number of tubes in one step: $N_{tubes_{1step}} = 618.$

Once the number of tubes containing the exchanger is solved it is necessary to know the number of steps that have to finish to dimensioning it. In order to dimension, we have to resort to heat transfer to evaluate and know the heat transfer rate.

In general, three different modes of heat transfer are recognized: conduction, convection and radiation.

Conduction is the heat transfer that is produced through a material medium by direct contact between its particles, when there is a temperature difference and by virtue of the movement of its micro particles. The amount of heat transferred by conduction is given by the Fourier law. This law states that the rate of conduction of heat through a body per unit cross-section is proportional to the temperature gradient that exists in the body.

Convection heat transfer consists of two simultaneous mechanisms. The first is heat transfer by conduction, due to molecular motion, to which energy transfer is superimposed by the movement of fluid fractions that are driven by an external force, which may be a density gradient (convection Natural), or a mechanically produced pressure difference (forced convection) or a combination of both. The amount of heat transferred by convection is governed by Newton's law of cooling

Radiation can be attributed to changes in the electronic configurations of the constituent atoms or molecules. In the absence of a medium, there is a net transfer of heat by radiation between two surfaces at different temperatures, because all surfaces with finite temperature emit energy in the form of electromagnetic waves. The heat emitted by a surface in the unit of time, is given by the law of Stefan-Boltzmann.

In the resolution of this project will be used experimental approaches by dimensional analysis to scale laboratory results so the following dimensionless numbers will appear:

- Nusselt: is the dimensionless coefficient of heat transfer by convection and represents the relation between the transfer of convection and the transfer of heat if it occurs only by conduction.
- Reynolds: expresses the relationship between inertial stresses (associated with increasing momentum in a moving fluid) and viscous stresses (associated with the internal resistance to the movement of a fluid, caused by friction of the molecules being slide over each other).
- Prandtl: it expresses the relation between the molecular diffusivity of the amount of movement and the diffusivity of the heat.
- Grashof: represents the relationship between the thrust forces and the viscous forces acting on the fluid. It is an indicative of the flow regime in natural convection, equivalent to the number of Reynolds in forced convection.
- Rayleigh: when the Rayleigh number is below a certain critical value (Ra <10), heat transfer occurs mainly by conduction, when it is above the critical value (Ra > 1000), the heat transfer occurs mainly by convection. $Ra = Gr \cdot Pr$.

Once the phenomenon has been explained, it is necessary to obtain such properties of gases and air. The air properties can be obtained directly with any program, but for those of gases it is necessary to take into account what each gas represents with respect to the total gases, so, it will be necessary to perform a weighted average using its molar fraction.

For example to calculate the density:

$$\rho_{gases} = \sum \frac{kmol_{gases,i}}{\sum kmol_{gases,i}} \rho_{gas,i}\left(T_{m_g}\right) \qquad \textbf{eq. 30}$$

As the same way at before, the properties are evaluated at the average temperature. The properties to calculate are density, viscosity, molar mass, Prandtl number and conductivity.

The number of steps to be taken by the preheater will have to be calculated through the heat exchanged, which depends on the conductance of the equipment and, in turn, on the exchange area and, therefore, the number of steps.

At first, the exchange area of the gases and of the air is:

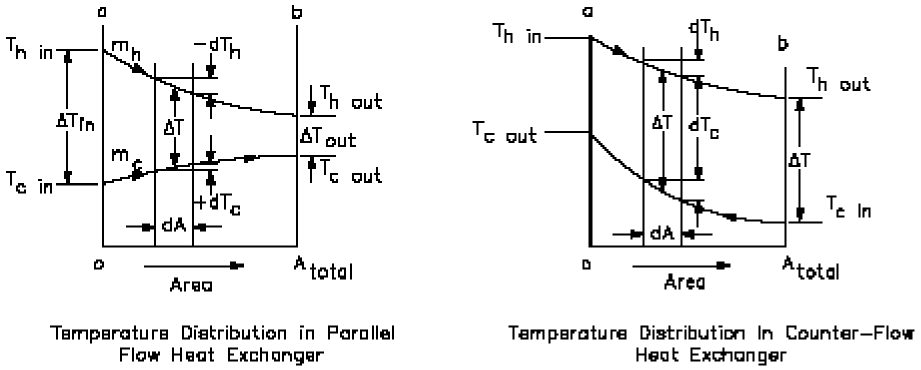
$$A_{gases} = N_{tubes_{1step}} \cdot N_{step} \cdot \pi \cdot D_{tube} \cdot L_z \qquad \textbf{eq. 31}$$

$$A_{air} = N_{tubes_{1step}} \cdot N_{step} \cdot \pi \cdot D_{nom} \cdot L_z \qquad \textbf{eq. 32}$$

To calculate the heat transferred in the tube exchanger, an energy balance is applied using Newton's Cooling Law. Since taking the average temperature of the fluid in the tube bank overestimates the heat transfer, that is why the "logarithmic mean temperature" is used. That method is called LMTD and allows dimensioning a heat exchanger that achieves a specific temperature change of a known mass flow fluid stream. To estimate the best value for the temperature difference ΔT_m governing the heat transfer, by means of an energy balance, we conclude that for parallel flow or counter flow heat exchangers; it is the mean logarithmic temperature difference between the inlet section and the outlet section of the exchanger.

For certain input and output temperatures, the mean logarithmic difference in temperature is higher in a counter-flow than in a parallel flow (i.e., to exchange the same heat requires a smaller surface area, so in our case, flow will be counter-flow).

The reason why the counter flow is best used for energy is the figure 10.



Temperature Distribution in Parallel Flow Heat Exchanger

Temperature Distribution In Counter–Flow Heat Exchanger

Figure 10. Temperature profiles in parallel and counter-flow heat exchanger

The temperature profiles of the two heat exchangers indicate two major disadvantages in the parallel-flow design. First, the large temperature difference at the ends causes large thermal stresses. The opposing expansion and contraction of the construction materials due to diverse fluids temperatures can lead to eventual material failure. Second, the temperature of the cold fluids exiting the heat exchanger never exceeds the lowest temperature of the hot fluid. This relationship is a distinct disadvantage purpose is to raise the temperature of the cold fluid.

The design of a parallel flow heat exchanger is advantageous when two fluids are required to be brought to nearly the same temperature.

The counter-flow heat exchanger has three significant advantages over the parallel flow design. Firs, the more uniform temperature difference between the two fluids minimizes the thermal stresses throughout the exchanger. Second, the outlet temperature of the cold fluid can approach the highest temperature of the hot fluid. Third, the more uniform temperature difference produces a more uniform rate of heat transfer throughout the heat exchanger.

Once the flow of a counter-flow is better in our design, we must take into account a correction factor since it could have more than one step, but in our case it will not be so. There is only one passage per shell and being flow counter-flow, the correction factor is $F = 1$.

$$\dot{Q}_{pre} = U_{gases} \cdot A_{gases} \cdot \Delta T_m \cdot F \qquad \textbf{\textit{eq. 33}}$$

$$\Delta T_m = \frac{T_{out_g} - T_{ent_{air}} - \left(T_{ent_g} - T_{out_{air}}\right)}{ln\left[\frac{T_{out_g} - T_{ent_{air}}}{T_{ent_g} - T_{out_{air}}}\right]} \qquad \textbf{\textit{eq. 34}}$$

For the calculation of the conductance of the gases, the thermal resistances are grouped, so we have the resistance of the gases, of the tube and finally of the air. When grouping them the expression is the following:

$$\frac{1}{U_{gases} \cdot A_{gases}} = \frac{1}{h_{gases} \cdot A_{gases}} + \frac{ln\left[\frac{D_{tube}}{D_{nom}}\right]}{K_{tube} \cdot 2 \cdot \pi \cdot L_z \cdot N_{tubes_{1step}} \cdot N_{step}} + \frac{1}{h_{air} \cdot A_{air}} \qquad \textbf{\textit{eq. 35}}$$

With the above equations it is only necessary to know the coefficient of transmission of gases and air in order to know the number of steps necessary for the heat transfer to be fulfilled.

In the case of gases, the procedure is as follows. First of all, to be able to a correlation obtain by experiments, in this case one of outside forced convection, it is necessary to characterize the gas flow. For this, the number of Reynolds is used. In this case, in a set of tubes, the characteristic speed that dominates the flow is the maximum speed V_{max} that is reached in the tubes, instead of the velocity V of approximation, therefore Re is defined on the V_{max}.

To know the Reynolds number is necessary to obtain that V_{max} by the gases flow.

$$\dot{m}_{gases} = \dot{n}_{fuel} \cdot \left(\sum kmol_{gases,i}\right) \cdot MolarMass_{gases} \qquad \textbf{eq. 36}$$

$$v_{gases} = \frac{\dot{m}_{gases}}{\rho_{gases} \cdot MolarMass_{gases} \cdot L_z \cdot L_x} \qquad \textbf{eq. 37}$$

$$V_{max_{gases}} = \frac{S_x \cdot v_{gases}}{S_x - D_{tube}} \qquad \textbf{eq. 38}$$

Solving the above equations yields a maximum velocity of 7,84 m/s and with that a Reynolds number of 5290, transition flux. Now, we are able to use one appropriate correlation taking into account that is a transition flux and it’s an outside forced convection.

$$Nu_{gases} = h_{gases} \cdot \frac{D_{tube}}{K_{gases}} = 1{,}13 \cdot C_1 \cdot Re_{gases}{}^{m} \cdot Pr_{gases}{}^{(1/3)}, \text{where } C_1 = 0{,}229 \text{ and}$$

$$m = 0{,}632 \qquad \textbf{eq. 39}$$

With that equation, the coefficient of transmission of gases is: $h_{gases} = 77{,}83\ W/m^2 \cdot K$

In the case of air, since it circulates inside the tubes, the convection is forced inside. And as the same as before, to be able to a correlation obtain by experiments, it is necessary to characterize the air flow using the Reynolds number. Now, it is not necessary to use the maximum speed since it is constant.

$$Re_{air} = \frac{4 \cdot \frac{\dot{m}_{air}}{N_{tubes_{1step}}}}{\pi \cdot D_{nom} \cdot \mu_{air}} \qquad \textbf{eq. 40}$$

$$\dot{m}_{air} = \dot{n}_{air} \cdot MolarMass_{air} \qquad \textbf{eq. 41}$$

Solving: $Re_{air} = 7649$. As before, the flow in this case is of transition, but the correlation is different since the convection is forced inside:

$$Nu_{air} = h_{air} \cdot \frac{D_{nom}}{K_{air}} = \frac{\frac{f_{air}}{8} \cdot (Re_{air} - 1000) \cdot Pr_{air}}{1 + 12{,}7 \cdot \left[\frac{f_{air}}{8}\right]^{0{,}5} \cdot \left(Pr_{air}{}^{(2/3)} - 1\right)} \qquad \textbf{eq. 42}$$

$$f_{air} = (0{,}79 \cdot ln(Re_{air}) - 1{,}64)^{-2} \qquad \textbf{eq. 43}$$

As we can see, the correlation changes and in this case the friction factor of the air is taken into account. When solving we obtain a coefficient of heat transmission of $h_{air} = 34{,}97\, W/m^2 \cdot K$.

Once we have obtained the coefficients of transmission, it is necessary to go back, to obtain the necessary number of steps solving the followings equations:

$$\dot{Q}_{pre} = U_{gases} \cdot A_{gases} \cdot \left(\frac{T_{out_g} - T_{ent_{air}} - \left(T_{ent_g} - T_{out_{air}}\right)}{ln\left[\frac{T_{out_g} - T_{ent_{air}}}{T_{ent_g} - T_{out_{air}}}\right]} \right) \qquad \textbf{eq. 44}$$

$$\frac{1}{U_{gases} \cdot A_{gases}} = \frac{1}{h_{gases} \cdot A_{gases}} + \frac{ln\left[\frac{D_{tube}}{D_{nom}}\right]}{K_{tube} \cdot 2 \cdot \pi \cdot L_z \cdot N_{tubes_{1step}} \cdot N_{step}} + \frac{1}{h_{air} \cdot A_{air}} \qquad \textbf{eq. 45}$$

Clearing the number of tubes of the equation, we obtain its value $N_{step} = 4{,}84$. Being a decimal value, it is necessary to approximate it, in this case to the upper value so that the heat yielded by the gases is fulfilled, since if we round to the lower number, that heat would be lower by losing some performance and, therefore, lack of savings. As stated above, the number of steps in the heat exchanger is 5.

With the number of steps in the heater, the length of said exchanger can be calculated in the direction of gas velocity, ie, the y direction.

$$L_{tot} = N_{step} \cdot \left[N_y \cdot D_{tube} + \left(N_y - 1\right) \cdot \left(S_y - D_{tube}\right)\right] = 16{,}9\ m \qquad \textbf{\textit{eq. 46}}$$

A factor to be taken into account is the pressure drop that occurs both in the pressure of the gases and in the air, due to the friction of the fluid against itself and against the walls of the tube, both by the exterior and by inside. Load losses in a straight conductor or primary losses are load losses due to the friction of the fluid against itself and against the walls of the straight pipe.

To know these losses, an experimental method is used, using the Darcy-Weisbach equation, together with the friction factor used previously and obtained by means of experimental equations or correlations.

$$\Delta P = f \cdot \frac{L}{D} \cdot \frac{v^2}{2g} = f \cdot \frac{L}{D} \cdot \rho \frac{v^2}{2} \qquad \textbf{\textit{eq. 47}}$$

In the case of air the friction factor is already known before, and in the case of gases is as follows:

$$f_{gases} = \left[0{,}176 + \frac{0{,}32 \cdot \frac{S_x}{D_{tube}}}{\left(\frac{S_x}{D_{tube}} - 1\right)^{\left(0{,}43 + 1{,}13 \cdot \frac{D_{tube}}{S_x}\right)}}\right] \cdot {Re_{gases}}^{-0{,}15} = 0{,}2255 \qquad \textbf{\textit{eq. 48}}$$

Applying the Darcy-Weisbach equation:

$$\Delta P_{air} = f_{air} \cdot N_{step} \frac{L_z}{D_{nom}} \cdot \frac{\rho_{air} \cdot {v_{air}}^2}{2} \cdot MolarMass_{air} = 494{,}5\ Pa \qquad \textbf{\textit{eq. 49}}$$

$$\Delta P_{gases} = f_{gases} \cdot N_{step} \cdot N_y \cdot \frac{\rho_{gases} \cdot {v_{gases}}^2}{2} \cdot MolarMass_{gases} = 1374\ Pa \qquad \textbf{\textit{eq. 50}}$$

The pressure drop is very small being greater in the gases, since the tubes that have to cross make them very difficult to pass through. Due to the loss of pressure it is necessary to install a forced draft fan that projects the air into the preheater. Assuming that this fan has an isentropic efficiency of 80%, the increase of electric consumption to activate this mechanism is:

$$\dot{W}_{air} = \dot{m}_{air} \frac{\Delta P_{air}}{\rho_{air} \cdot MolarMass_{air} \cdot \eta_s} = 1937\ W \qquad \textbf{\textit{eq. 51}}$$

5.3. Calculation of energy saving

Once designed in heater, the primary objective is to know the energy saving in fuel that involves the installation of the air heater. The air used to the combustion now enters warmer therefore its enthalpy will increase and with it the balance realized previously also.

$$\dot{E}_{fuel} + \dot{E}_{air} = \dot{Q}_{useful} + \dot{E}_{gases} \qquad \textbf{eq. 52}$$

In this case, the temperature of the fuel and the temperature of the exhaust gases is the same as before, but the air inlet temperature is higher. So the maximum temperature at which we designed the heater so that no acid is produced at its outlet is $351{,}3\ ℃$.

$$\dot{E}_{fuel} = \dot{n}_{fuel} \cdot \left(\sum kmol_{fuel,i} \cdot h_{fuel,i}\left(T_{fuel,i}\right)\right) \qquad \textbf{eq. 53}$$

$$\dot{E}_{air} = \dot{n}_{fuel} \cdot \left(kmol_{O_2} \cdot h_{O_2}\left(T_{e,air}\right) + kmol_{N_2} \cdot h_{N_2}\left(T_{e,air}\right)\right) \qquad \textbf{eq. 54}$$

$$\dot{E}_{gases} = \dot{n}_{fuel} \cdot \left(\sum kmol_{gases,i} \cdot h_{gases,i}\left(T_{out\,gases,i}\right)\right) \qquad \textbf{eq. 55}$$

Applying the previous energy balance, we get the new fuel consumption: $\dot{n}_{fuel} = 0{,}00576\ \mathrm{kmol/s}$.

To obtain the fuel consumption per hour under normal conditions: $(\mathrm{T_n} = 25\ ℃; \mathrm{P_n} = 1\ \mathrm{atm})$

$$\dot{V}_{fuel_{hour}} = \frac{\dot{n}_{fuel} \cdot R \cdot T_n}{P_n} \cdot 3600 = 464{,}8\ m^3/hour \qquad \textbf{eq. 56}$$

In the event that the company works 800 hours a year, the annual consumption will be:

$$\dot{V}_{fuel_{year}} = \dot{V}_{fuel_{hour}} \cdot 8000 = 3{,}718 \cdot 10^6 m^3/year \qquad \textbf{eq. 57}$$

If we compare the fuel consumption before consumption by installing the air heater, we see that it decreases considerably, specifically, $667913\ \mathrm{m^3/año}$ of fuel. What comes to be 15,23 %. Actually, the price of the natural gas is around 0,05 €/kWh, so the savings of the company would be about 391,000 €.

6. Design of the communication of the preheater with the kiln

6.1. Calculation of the pipe diameter

Once we have designed the preheater it is necessary to conduct that hot air to the furnace for its subsequent reaction with the natural gas for combustion. We have to design a pipe to transport the air up there like in the figure 10.

The length of said pipe has to be 32 meters and as before, the air speed must be about 10 m/s.

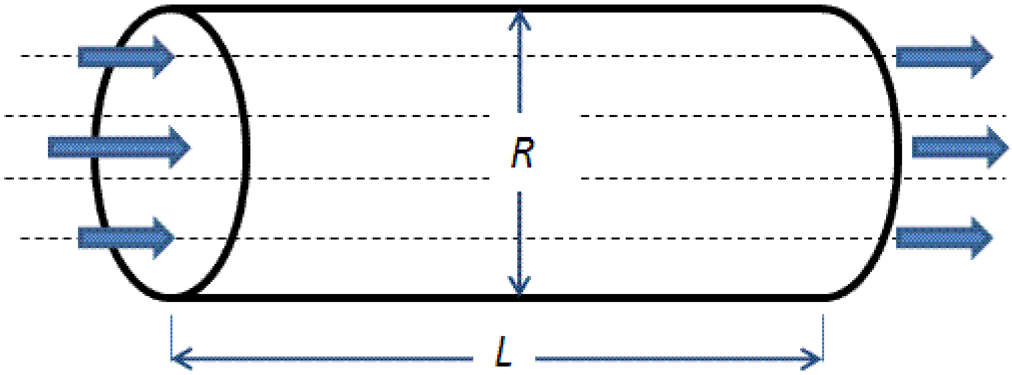


Figure 11. Example of pipe with an air flow

The calculation of the diameter of the air pipe from the preheater to the furnace will be calculated from the continuity equation in the pipe, which relates the volumetric flow rate (calculated at the new air temperature) to the velocity and the section.

$$\dot{V}_{air} = \frac{\dot{n}_{air}}{\rho_{air}} = \frac{v_{air}\cdot\pi\cdot D_{pipe}}{4} \qquad \textit{eq. 58}$$

Solving the eq. 58, we can obtain that the diameter of the pipe has to be $\mathrm{D_{pipe}} = 73{,}52\ \mathrm{cm}$. The pipe is made of the same material as the tubes of the exchanger.

6.2. Calculation of the necessary insulation

Since the pipe is made of metal, the air will lose a lot of temperature until it reaches the furnace; therefore it is necessary to line the pipe with insulation to maintain the temperature of the air. The insulation is made of rock wool chill which has a thermal conductivity of $K_{ins} = 0{,}04\, W/m \cdot K$.

It is necessary to calculate the thickness of insulation to be placed around the pipe so that the heat lost is not too high. To do this, heat transfer must be used; in this case four forms of heat exchange must be considered: forced convection inside the pipe, conduction in the pipe thickness and in the thickness of the insulation, and external forced convection out of the insulation.

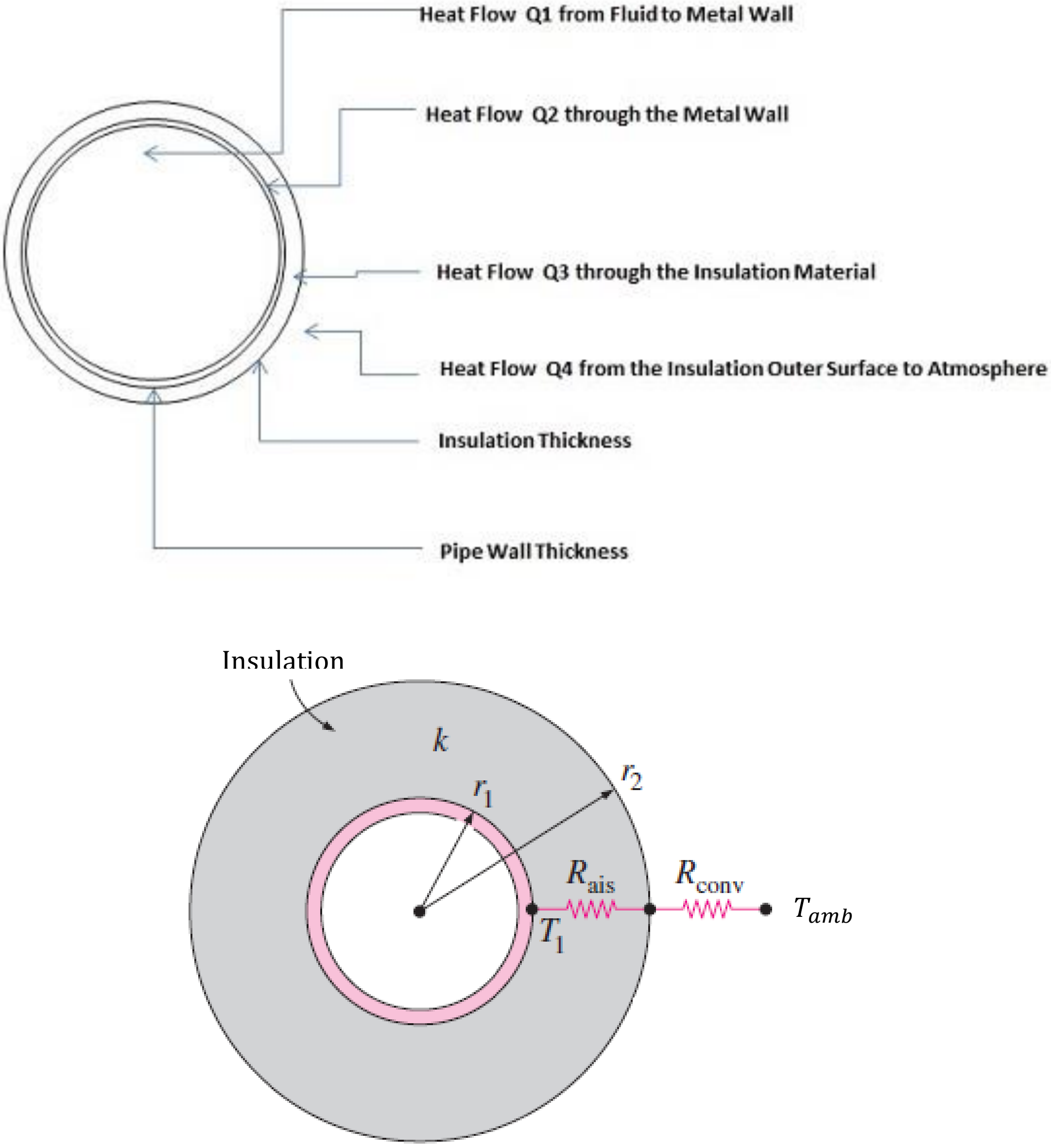


Figure 12. Insulation in a pipe

The heat exchanged in the pipe is calculated as follows:

$$q_{pipe} = \frac{(T_{air} - T_{amb})}{R_{tot}} \qquad \textbf{eq. 59}$$

For them it is necessary to calculate the total thermal resistance as we can see in the figure 11.

$$R_{tot} = R_{ic} + R_{pipe} + R_{ins} + R_{ec} \qquad \textit{eq. 60}$$

The calculation of each of the thermal resistances is calculated as follows, using experimentally drawn correlations, as in the design of the heat exchanger. It is necessary to take into account that to calculate the properties of the air, they are evaluated at constant temperature, to which the air leaves the preheater

In the case of the forced convection inside the pipe and as the same as before, to be able to use a correlation obtain by experiments, it is necessary to characterize the air flow using the Reynolds number. Now, it is not necessary to use the maximum speed since it is constant.

$$Re_{air} = \frac{4 \cdot \frac{\dot{m}_{air}}{N_{tubes_{1step}}}}{\pi \cdot D_{nom} \cdot \mu_{air}} \qquad \textit{eq. 61}$$

Solving: $Re_{air} = 133208$. As before, the flow in this case is turbulent, so the correlation is the following:

$$Nu_{air} = h_{air} \cdot \frac{D_{nom}}{K_{air}} = \frac{\frac{f_{air}}{8} \cdot (Re_{air} - 1000) \cdot Pr_{air}}{1 + 12{,}7 \cdot \left[\frac{f_{air}}{8}\right]^{0{,}5} \cdot \left({Pr_{air}}^{(2/3)} - 1\right)} \qquad \textit{eq. 62}$$

$$f_{air} = (0{,}79 \cdot ln(Re_{air}) - 1{,}64)^{-2} \qquad \textit{eq. 63}$$

When solving we obtain a coefficient of heat transmission of $h_{air} = 14{,}34\, W/m^2 \cdot K$. In the case of internal forced convection, the thermal resistance is as follows:

$$R_{ic} = \frac{1}{h_{air} \cdot \pi \cdot D_{pipe} \cdot L_{pipe}} = 0{,}0009436\ m^2 \cdot K/W \qquad \textit{eq. 64}$$

In the conduction of the tube and the insulation the resistance they offer is calculated directly.

$$R_{pipe} = \frac{ln\left(\frac{D_{pipe} + 2 \cdot t_{pipe}}{D_{pipe}}\right)}{K_{pipe} \cdot 2 \cdot \pi \cdot L_{pipe}} = 0{,}00000168\ m^2 \cdot K/W \qquad \textit{eq. 65}$$

But in the case of the insulation, since we do not know the value of its thickness, we do not obtain a numerical value but later on we will obtain a table of how it varies depending on the heat released.

$$R_{ins} = \frac{ln\left(\frac{D_{pipe} + 2 \cdot t_{pipe} + 2 \cdot t_{ins}}{D_{pipe} + 2 \cdot \cdot t_{pipe}}\right)}{K_{pipe} \cdot 2 \cdot \pi \cdot L_{pipe}} \qquad \textit{eq. 66}$$

Consulting several tables and experiments can be considered that the coefficient of natural convection of the air is $10\ W/m^2 \cdot K$; but at the same way as before the resistance in the natural convection produced on the outside of the pipe cannot be a numerical value since it depends on the thickness of the insulation.

$$R_{ec} = \frac{1}{h_{amb} \cdot (D_{pipe} + 2 \cdot t_{pipe} + 2 \cdot t_{ins}) \cdot \pi \cdot L_{pipe}} \qquad \textit{eq. 67}$$

Adding all the resistances we get the total.

And as we mentioned before, the heat transferred to the environment depends on the value of the total resistance as follows.

$$q_{pipe} = \frac{(T_{air}-T_{amb})}{R_{tot}} \tag*{eq. 68}$$

Once we have all the above equations we can obtain a table to relate the heat released in the pipe according to the thickness of insulation placed. In table 2, it can be seen that the yielded heat decreases with increasing the value of the thickness of insulation, something that seems obvious, but it does not do it in a linear way, so it arrives a moment from which a very great thickness does not compensate.

Lost heat			
$e_{ais}\ [m]$	$q_{\text{tubería}}\ [kW]$	$e_{ais}\ [m]$	$q_{\text{tubería}}\ [kW]$
0,001	125,7	0,027	30,13
0,002	111,7	0,028	29,31
0,003	100,4	0,029	28,52
0,004	91,3	0,03	27,78
0,005	83,71	0,031	27,08
0,006	77,29	0,032	26,42
0,007	71,8	0,033	25,79
0,008	67,05	0,034	25,19
0,009	62,9	0,035	24,62
0,01	59,24	0,036	24,07
0,011	56	0,037	23,55
0,012	53,09	0,038	23,05
0,013	50,48	0,039	22,58
0,014	48,12	0,04	22,12
0,015	45,98	0,041	21,69
0,016	44,02	0,042	21,27
0,017	42,23	0,043	20,87
0,018	40,58	0,044	20,48
0,019	39,06	0,045	20,11
0,02	37,66	0,046	19,76
0,021	36,35	0,047	19,41
0,022	35,13	0,048	19,08
0,023	34	0,049	18,76
0,024	32,94	0,05	18,45
0,025	31,95		

Table 2. Lost heat

Also the values of the table are represented in a graph, figure 12, in which we can see as explained above. A small value of thickness can cause us to lose too much heat, something unwanted since the air would arrive with less temperature of the desired one. On the other hand, a value too high in thickness does not compensate for the heat it retains because, for example to make the heat loss less than 25 kW, a great increase of insulation is necessary, something too expensive.

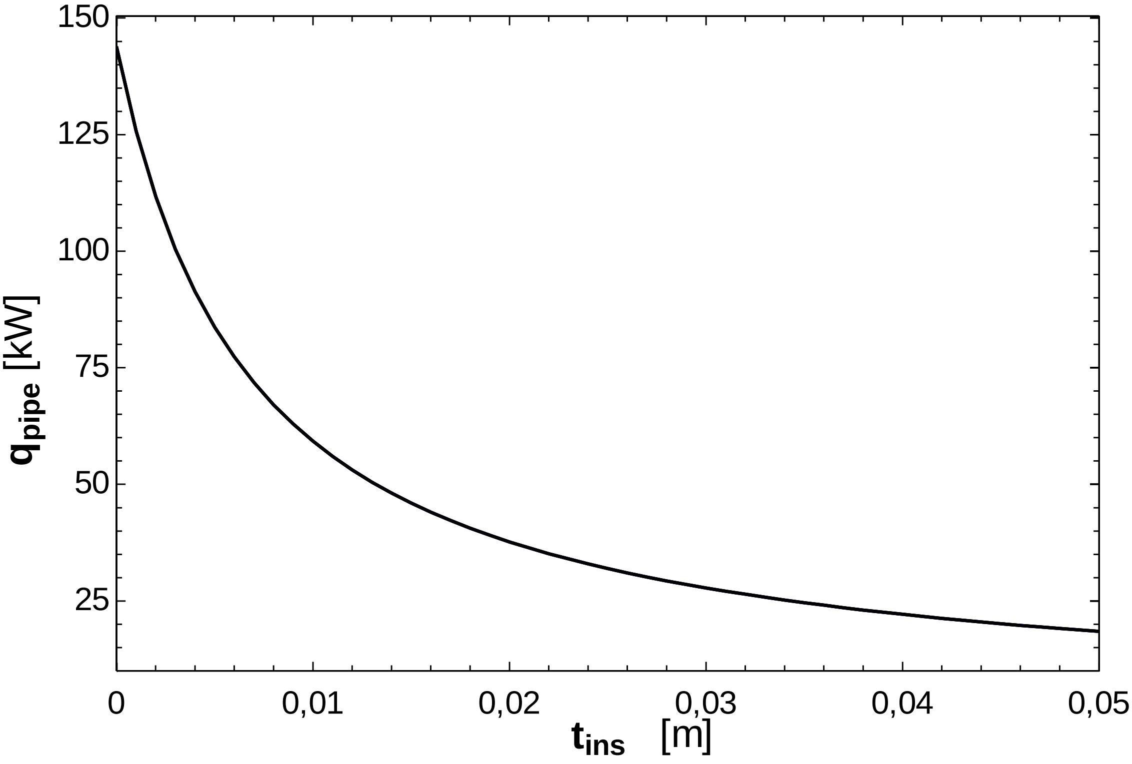


Figure 13. Lost heat

For example if we want the temperature on the outer face of the insulation does not exceed 40 ° C, the insulation thickness will be obtained by equalizing the heat yielded before the insulation layer and the heat gained by external convection

$$\frac{T_{air} - T_{ais}}{R_{ic} + R_{pipe} + R_{ais}} = \frac{T_{ais} - T_{amb}}{R_{ec}}$$

Obtaining a thickness of $\mathrm{t_{ins}} = 0{,}07333\ \mathrm{m}$.

7. Conclusion

In this project I have tried to apply the knowledge acquired in all my formation like engineer in order to calculate a good approximation to the analysis of the oven and to the design of the air preheater.

A mass and energetic analysis of the kiln installation has been carried out, which has allowed to obtain a 73,01% yield of the current installation.

A study of the different types of preheaters has been carried out and a design of a tubular preheater has been made, which allows to reduce exhaust gases losses. It reduces the combustion gases at

The stove has been dimensioned, which reduces the combustion gases at 250 °C and recovers $802{,}7\ kW$.

If we compare the fuel consumption before consumption by installing the air heater, we see that it decreases considerably, specifically, $667913\ \mathrm{m}^3/\mathrm{año}$ of fuel. What comes to be 15,23 %, saving about 391,000 €.

Finally, and to sum up, I have discovered a lot of information and knowledge doing this project and I really think that is going to help me in my future professional performance.

8. Literature

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