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MATHEMATICAL MODELSDESCRIBINGHEAT TRANSFER IN CERAMIC FURNACES

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ABSTRACT
The present work is a documentary investigation that addresses different types of mathematical models that explain or translate the heat transfer behavior in ceramic furnaces of different characteristics in order to obtain a clear criterion of which is the best mathematical modeling that in the application we allow timely optimization of resources to reach the necessary temperatures in heat treatments.

Keywords: coal combustion, hive oven, thermodynamic heat exchanger, heat transfer, convection, radiation.

1. INTRODUCTION

The firing stage is, in many respects, the most important of the ceramic tile manufacturing process. In firing, microstructural changes occur in the tiles that give them their final properties and appearance.

In many cases this process can be carried out by external mechanisms that create a thermal source that treats the characteristics until reaching the necessary conditions for the thermal change of the piece.

These so-called furnaces act in different ways according to their characteristics, compositional, and mechanical. In search of achieving greater unnecessary wear and optimization of the heat source whatever it may be, it has been chosen to make mathematical models that allow us to describe the transfer of energy, as more transcendental methods we can find models represented by finite equations methods, long furnace model, etc. Being these methods very complex applying calculations with differential equations.

We will give a global vision of the different types of kiln for heat treatment of ceramics according to each need.

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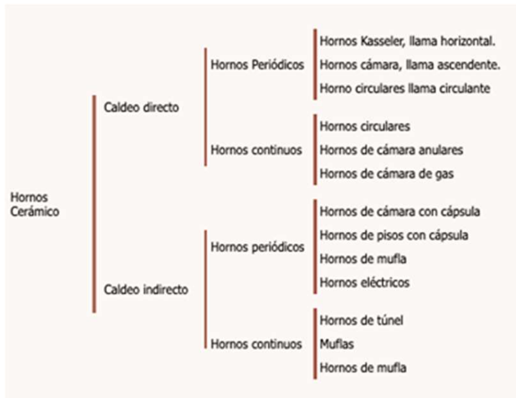

Figure 1: Types of ceramic kilns
Source: All Culture

Pottery and ceramic kilns in Spain are structures or factories of varying complexity, size and appearance, intended for firing clay pieces. The traditional model is an enclosure with a vaulted roof provided with a chimney and one or more mouths to load fuel, usually firewood, and objects that you want to cook.

The function of the kiln, the firing or firing of ceramic material, is one of the fundamental steps of the pottery process, the one with the greatest magical sense and the most decisive in obtaining the final product.

(Bedillo, Antonio 2008).

1.1. Heat transfer

Heat transfer, in a physical medium, is the process by which heat energy is exchanged between different bodies, or between different parts of the same body that are at different temperatures. Heat is transferred by convection, radiation or conduction. Although these three processes can take place simultaneously, it may happen that one of the mechanisms predominates over the other two. Forexample, heat is transmitted through the wall of a house mainly by conduction, water from a saucepan on a gas burner is heatedto a large extent by convection, the Earth receives heat from the sol almost exclusivelyby radiation. Insulation serves to retard the transfer of heat outside or within a conditioned environment. In cold media, the aim is to keep the warm air inside is to stop or at least slow the movement of cold air from outside. In a hot environment, the objective is reversed, but the principles of heat transfer delay remain constant, regardless of the direction of heat flow, the next system of units is used.
(Salamanca, Arturo 2015).

Q: Caloric flow cup [KW]
q: Rate of caloric flow per unit area [KW/m]

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The heat transfer mechanismsare as follows:

1.2. Conduction

In solids, theonly form of heat transferis conduction. If an ex tremo of a metal rod is heated so as to increase its temperature, the heat is transmitted to the coldest extremo by conduction. The ex act mechanism of heat conduction in solids is not fully understood, but it is believed to be due, in part, to the movement of free electrons whichcarry energy when thereis a difference in temperature. This theory explains why good electrical conductors also tend to be good conductors of heatr. In 1233, the French mathematician Joseph Fourier gave aprecise mathematical explanation known as F ourier's lawof heat conduction. This law states that the speed of heat conduction througha body per unit cross-section is proportional to the temperature gradient in the body with the sign changed. The proportionality factoris called the thermal conductivityof the material. Materials such as gold, silver or copper have high thermal conductivities and conduct heat well, while materials such as glass or asbestos have hundreds and even thousands of times lower conductivities do not conduct much heat, and are known as insulators. The conductivitiesin ceramics are very low and serve as refractory materials. In engineering it is necessary to know the speed of heat conduction through a solid in which thereis a known temperature difference. To find out, very complex mathematical techniques are required, especially if the process varies over time in this case, it is a transient tea conduction habla. With the help of specialized ADO software, these problems can be solved today even for bodies of complicated geometry.
(Salamanca, Arturo 2015).

$$(1) Q = \lambda A \frac{\Delta T}{\Delta S}$$

1.3. Convection

Ifthere is a temperature difference inside a liquid or gas, there will almost certainly be movement of the fluid. This movement transfers heat from one part of the fluid to another by a process called convection. The movement of the fluid can be natural or forced. Ifa liquid or gas is heated, its density and mass per unit volume usually decreases. If the liquid or gas is in the gravitatory field, the hotter and less dense fluid rises, whilethe cooler and denser fluid descends. This type of movement, due exclusivelyto the non-uniformity of the temperature of the fluid, is called natural convection. Forced convectionis achieved by subjecting the fluid to a pressure gradient, thereby forcingits motion according to the lawsof fluid mechanics. The heating of a h abitation by means of a radiator depends not so much on the radiation as on the natural currents of convection, which allow the warm air to rise h acia the tec h o and the cold air of the rest of the h abitation to be directed by hacia theradiator. Sincewarm air tends to rise and cold air to fall, radiators should be placed close to the ground and air conditioners close to the techo so that efficiency is maximum. In the same way, natural convection is responsible for the ascension of hot water and steam in natural convection boilers, and for the draft of theimeneas. Convection also determines the

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movement of large air masses on the Earth's surface, the action of winds, cloud formation, ocean currents and heat transfer from the interior of the Earth's surface.
(Salamanca, Arturo 2015).

$$(2)\ Q = h\ A\ \Delta T$$

1.4. Radiation

It is the transfer of heat, in the form of electromagnetic energy, through space.
Radiation presents a fundamental difference with respect to conduction and convection, the substances that exchange heat do not have to be in contact, but can be separated by a vacuum. Radiation is a term that is applied genericallyto all kinds of phenomena related to electromagnetic waves. Se must take into account principles such as Leand Stefan all objects emit radiant energy, whatever their temperature, consider the transfer of radiation by a surface of area a, which is at a temperature T, the radiation emitted by the surface, is produced from the thermal energy ofmatter limited by the surface. The speed at which energy is released is called radiation power a, its value is proportional to the fourth power of
the absolute temperature. This is known as Stef's lawfan that where

$\sigma = 5{,}67x10\text{-}8\ W/m^2k^4$

It is called Steffan Boltzmann's constant and ε is a radioactive property of the surface called emissivity, its values vary in the range C < ε
G 1, is a measure of the efficiency with which the surface emits radiant energy, depends on the material.

Figure 2: Thermal Emissivity Table
Source: Salamanca Arturo

2. HEAT TRANSFER MODELS

The general heat transfer model to be taken into account for the Horno is as follows:

$$(3)\qquad Q_{combustible} = Q_{perdida} + Q_{residuos} + Q_{materia\ prima}$$

The specifications of each material from which the H orno is designed have to be recognized and also the temperatures between walls are verified and the following equations are obtained.
Between T_3 and T_1 with the dimensions of their respective geometries, then we pass to the next propagation medium which is the continuous wall, obtaining the following equation.

ϵ es adimensional

Material	Emisividad	Temperatura °C
cemento	0,96	0-200
cemento rojo	0,67	1371
ladrillo refractario	0,38	1000
Acero	0,06-0,25	(-70) - 700
Pintura verde	0,92	24
pintura gris	0,96	24

In addition, for the development of the model it is assumed that:

- The flow is stationary.
- The physical properties of flue gases vary with temperature.
- Heat transfer between gas and products and gas and walls is by convection and radiation.
- The temperature of the products, walls and gases is uniform inside the oven.
- Coal supply is a function of time.
- The accumulation of water present in the products is not taken into account.
- Variations by kinetic and potential energy are neglected.
- Medium participating in radiation, using radiation models of an isothermal gray gas in an enclosure formed by two gray surfaces and radiation between a gas and an enclosure of a single gray surface.

(Jimenez and Jaramillo 2018).

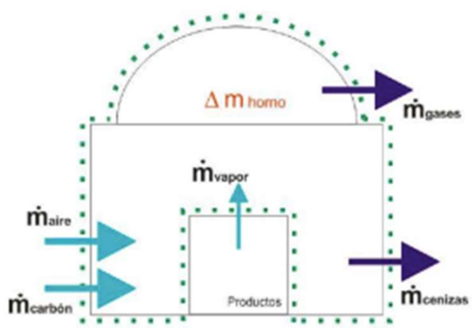

Figure 2: Mass flow in furnace
Source: Jiménez and Jaramillo 2018

Resolution algorithm

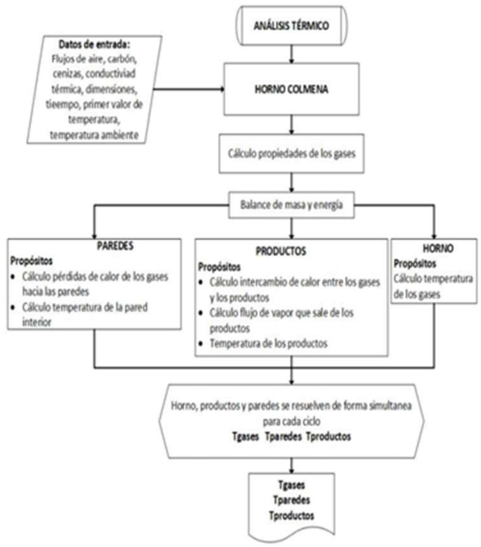

Figure 3: Solution gram flow
Source: Jiménez and Jaramillo 2018

2.1. Mathematical model of the calcination process of basic nickel carbonate

Journal of Mining and Geology Vol. XVI I,
The energy balance approach for a differential of the hornor:

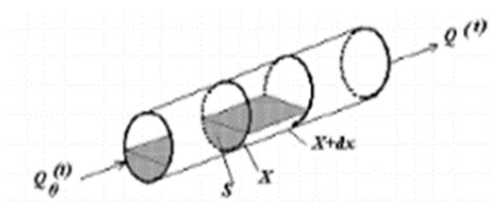

Figure 4: Diagram for the conformation of the mathematical model of calcination.
Source: Columbie, Rodríguez, Guzmán and Sevilla,2000

(4) $$\rho c S dx \frac{\delta\theta(x,t)}{\delta t} = c[Q(x,t)\theta(x,t) - Q(x+dx,t)\theta(x+dx,t)] + k_1 dx[\theta_g(x,t) - \theta(x,t)] + k_2 dx[\theta_p(x,t) - \theta(x,t)]$$

where:
ρ: Solid density, kg/m3
C: Specific heat of the solid, J/kg K
S: Solid cross section, m2
$\theta, \theta_g, \theta_p$:Temperature of solid, gas and wall respectively, K
k_1:Surface coefficient of heat transfer from gas to solid per unit length, W/mK

k_2:Surface coefficient of heat transfer from wall to solid per unit length, W/mk

In expression (4) the left part characterizes the rate of variation of the temperature q (t) of the material element dx; the first member of the right part is the heat that enters with the flow of material Q to the element dx; the second is the heat that leaves with the material; the third and fourth members
they are the heat delivered by the gases and the wall to the material according to the Newton-Richman law.
For the determination of the coefficients it is necessary to take into account the forms of heat transfer present in the calcination furnace. Heat from gas to solid is transmitted by radiation and convection (Arliuk 1985, Brimacombe and Watbmison 1978a, Brimacombe and Watbmison 1978b, Detkov 1986) and the following expression is valid for the heat transfer coefficient.$k_1\ y\ k_2$
(5)

$$\alpha_{gs} = \alpha_g + \frac{c_o \varepsilon_{red}(\theta_g^4 - \theta^4)}{(\theta_g - \theta)}$$

Where the second term on the right takes into account the heat transfer by radiation and the coefficient the heat transfer by convection. α_g
In this casec_0 : Black body radiation coefficient, W/m2K4
α_g- Convection heat transfer coefficient, W/m2K

(6)

$$\varepsilon_{red} = \frac{\varepsilon_s \hat{\varepsilon}_g}{\varepsilon_s + \widehat{\varepsilon}_g(1 - \varepsilon_{s)}}$$

Itis the reduced degree of integral radiation.
ε_s:Emissivity of the solid
ε_g:Gas emissivity plus carryover

For the determination of the heat transfer coefficient by convection from gas to solid, the common equation for the turbulent motion of a gas in straight and round tubes can be used.

(7)$N_u = 0.021 Re^{0.8} Pr^{0.4} \Psi$

Where:
$N_u = (\alpha_g\ deq)/\lambda_g$ according to Nussel's criteriont.

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λ_g :Thermal conductivity of gas, W/m k

deq=(4S) /U: Equivalent diameter, m

S: Furnace cross-sectional area, m2

U: Total interior perimeter of the furnace, m

P_r: Prandtl criterion

Re: Reynolds criterion

$\psi = 1.38(\frac{1}{deq})^{-0,12}$adjustment coefficient.

Therefore:

(8)$\alpha_g = 0.021(\frac{\lambda_g}{deq})Re^{0.8}Pr^{0.4}\Psi$
All parameters in expression (8) must be taken at gas temperature.

The Reynolds number

(9)$Re = \frac{4\,V_g(1+\omega)}{\pi\, d_{eq}\xi\eta_g}$

where:

V_g:Gas velocity, m/s
ω: Moisture content in the gas, kg humidity / kg dry gas
η_g:Dynamic viscosity coefficient, kg/m s
ξ: Degree of filling the furnace with solid

The equivalent diameter deq is the inner diameter of the dint furnace.
The filling coefficient of the oven isξ:

(10)$\xi = \frac{S}{S_r}$

where:
S: is the cross-sectional area occupied by the solid, m2

S_T:is the total cross-sectional area of the furnace, m2 .

For the determination of it is necessary to define the function b = f(Q) for which is the area of the cross section occupied by the solid from the double integral, as followsξ:

(11) $S = \int_{-R\sin}^{R\cos\beta} dx \int_{\sqrt{R^3X^3}}^{0} dy = \int_{-R\sin}^{R\cos\beta} \sqrt{R^2 - X^2}\, d_x = \frac{R^2}{2} \operatorname{csch} \frac{X}{R} [_{-R\sin}^{R\cos} + \frac{X}{2}\sqrt{R^2} - X^2]_{-R\sin}^{R\cos\beta} = R^2\beta + R^2 \sin\beta\cos\beta = R^2(\beta + \frac{\sin 2}{2})$

Assuming sen2β = 2 we get: β

(12)$S = 2R^2\beta$

taking into account that the charge of the solid is
(13)$Q = S\rho V$

is obtained

(14)$\beta = \frac{Q}{2R^2\rho V}$

The expression (14) relates the angle b to the charged load β = f(Q).

The linear velocity of the solid according to expression developed at the Leningrad Institute of Mines
Where:

φ: Angle of inclination of the oven;
V: Oven rotation speed;
D: Diameter of the oven.

The Prandtl number is determined by:

(15)$Pr = \frac{\eta_g c_g}{\lambda_g}$

where:
η_g: heat capacity of wet gas J/ kg K
c_g: Dynamic viscosity coefficient, kg/m h;
The dynamic viscosity of wet gas is determined according to:

(16)$\eta_g = 0{,}36\left[0.1603 + 0{,}44634(0.001t_g)^2 + 0{,}0319(0{,}001t_g)^3\right]$

The specific heat or heat capacity of the wet gas is determined by: c_g

(17)$C_g = \frac{C_{gs}+C_{vk}\omega}{1+\omega}$

Being
c_{gs}:is the heat capacity of the dry gas;
c_{vh}:is the heat capacity of water vapour.

And according to (Rioshkevich, Podkorbinshy and Rejnik 1979)
(18)$C_{vs} = 0{,}442 + 0{,}0755\left(0{,}001t_g\right) + 0{,}142(0.001t_g)^2 + 0{,}066(0.001t_g)^3$
(19)$C_{vs} = 0{,}239 + 0{,}0202\left(0{,}001t_g\right) + 0{,}142(0.001t_g)^2 - 0{,}302(0.001t_g)^3$

and gas conductivity:

(20)$\lambda_g = C_{vs} = 0{,}01964 + 0{,}07296\left(0{,}001t_g\right) + 0{,}0012(0.001t_g)^2 - 0{,}00022(0.001t_g)^3$

2.2. Energy transfer mechanisms in roller furnaces

2.2.1. Transfer between gases and internal surfaces

It is generally accepted that there are two mechanisms by which the transfer of energy between gases and the interior surfaces of the furnace occurs: convection and radiation.
Convection occurs as a result of contact between gases and the interior surfaces of the furnace. Convection is associated with a flow of matter from the surface to the heart of gases (or vice versa). A distinction is made between natural convection and forced convection, which may overlap. In the case of natural convection, the flow of matter is due exclusively to variations in density resulting from differences.
of temperature, while in forced convection it is the action of an external force (pressure difference) that sets the fluid in motion. Inside roller furnaces forced conversionpredominates because of the turbulence generated by the burners and the turbulent gas circulation regime in general.
The heat flux Q reaching a surface by convection can be described by Newton's law of cooling:

(21) $Q = AhC\,(T - Tg)$

2.2.2. Transfer through walls and dissipation to the environment

The walls transmit heat through their sinus by conduction, which involves lattice vibrations and, in the case of metallic solids, migration of free electrons. To analyze the conduction through the walls of the furnace, it is usually considered that these are sheets of infinite extension and finite thickness. Under thisapproximation, we have Fourier's Law.

The MEF analysis of a thermal problemis based on the heat transfer equation in a body (Zhu and Chao, 2002).

(22)

$$\rho(T)c(T)\frac{\partial T}{\partial t} = q + \frac{\partial}{\partial x}\left[Kx(T)\frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[Ky(T)\frac{\partial T}{\partial y}\right] + \frac{\partial}{\partial z}\left[Kz(T)\frac{\partial T}{\partial z}\right]$$

As it follows, the thermal problem is governed by a nonlinear differential equation, because the thermophysical properties of the material are dependent on temperature. Heat losses to the surrounding environment by radiation and convection are considered using the equations
(Zhu and Chao, 2002)

(23)$qc = h(T - Too)$

(24)$qr = eB(T^4 - T\infty^4)$

where:
h = Convection coefficient or Film coefficient (W/(m2 - °C))
T = Ambient temperature (ºC) ∞
e =Body surface emissivity
B= Stef constantfan-Boltzmann (W/(m2 - ºC4)

2.2.3. Finite difference method

Finite differences (FDM), like MEF, is one of the universally applied numerical methods for solving differential equations using finite differential equations to approximate derivatives. Through a process of deratization, the infinite set of numbers represent the unknown function, and then be replaced by a finite number of unknown parameters. A finite difference is a mathematical expression of the form f(x + b) - f(x + a), where, if a finite difference is divided by b - a an expression close to the differential quotient is obtained, using finite quantities instead of infinitesimals.

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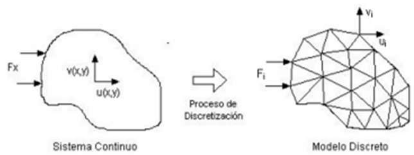

Figure 4: Engineering model
Source: Leal Armando 2016.

2.2.4. Iterative method

An iterative method is a mathematical procedure consisting of a series of successive approximations to the solution of a type of problem. Iterative methods are used to solve problems that have a large number of variables
There are two types of iterative methods, stationary methods and non-stationary methods.
Stationary methods are simple to understand and implement, but they are not very effective, while in non-stationary methods, analysis is more complicated, but they tend to be very effective. The most used stationary methods are the Jacobi and the Gauss - Seidel, the last one explained in the next section because it is the one of interest in this project.
(Leal, Armando 2016).

3. CONCLUSIONS

A mathematical model was developed to calculate it:

- A mathematical model was developed to calculate the temperature of the gases inside the hive furnace. The model took into account the phenomena of heat and mass transfer between gases and products, energy losses by the walls of the furnace and considered the variation of the physical properties of gases with temperature through a thermodynamic analysis of combustion. The mathematical model was validated with the experimental data.

- For the coal feeding, a mathematical approximation of the real process was used, since this is staggered and increases according to the operator's criteria, and the coal is not supplied to all mouths simultaneously.

- Five alternatives for the heat recovery system were pre-selected, based on the temperatures measured in the experimental study carried out at the company. The basic criteria to be taken into account in the design of the recovery system were defined.

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- It is recommended that the company maintain better control in the way coal is delivered to the furnace, as it is a critical variable in the cooking process, as demonstrated by the parametric analysis carried out with the model developed with constant coal delivery.

Through the simulation program, a Estudy of parametric optimization of various options that the program may vary, among them we have the
Composition of gas and ceramic pastes, number and size of modules, rollers, burners, inlet air flows and environmental conditions.

The effect of the quality of a natural gas in this type of furnace is not significant for the final result obtained: the final temperatures of the components of each module
They vary by only one-tenth of a degree in the worst-case case for different natural gases introduced. In
On the other hand, the amount of gas consumed does vary considerably from one gas to another, to compensate for their different calorific values (it can reach around 20% variation between the richest and poorest gases).
energetically of those supplied in Spain). The atmosphere resulting from the furnace also does not vary substantially from one to another gases studied:
major differences that are obtained are 0.2% of O_2 in the firewall area (logically it will be the area where you most notice the change of a supply gas), this variation is not problematic if the percentages of oxygen in the channel remain above safety margins. It can be said that the variation of stoichiometric air that supposes a change of gene. It is compensated by the variation -in the opposite direction- of the calorific value of the new gas, keeping the combustion air fixed.
The composition, format and cooking cycle of the pasta to be used is a data to be introduced in the program, therefore the effect of variation of any of these parameters can be studied.
Combustion air flows, such as cooling air, are
Fundamental parameters in the evolution of the simulation in the furnace. The flow of the primary air to the burners is responsible for the combustion phenomenon in the furnace. With a reasoning similar to that of combustion air, the importance of the appropriate choice of cooling air flows is denoted, depending on the ceramic load introduced (both weight and composition of the same). The necessary air will be blown so that the cooked pieces come out at 150º C, ensuring a very slow cooling around 570º C (allotropic transformation of quartz). The air flows must be in relation to the dimensions of the furnace that we simulate: if the furnace is very wide and has a very long channel, the combustion and cooling flows must also be high.
The number of oven modules can be varied at the user's will, within logical margins. Of
In this way, the effect of increasing the number of modules of any of the typical areas of the kiln: pre-kiln, kiln, different cooling zones, etc., on the final temperature curves of the ceramic paste can be studied. The economic savings could also be studied considering different sizes of the same, combining the cost of materials and the production obtainable in each case. The zones that can be varied, which will then be shown in the user manual of the program, are as follows:

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(1) Area of modules located between the two tubes of the
Smoke extraction chimney.
(2) Module zone between the burner area of
Pre oven and the second tube of the suction chimney
Smoke.
(3) Pre-oven zone: lower burners.
(4) Oven area: upper and lower burners.
(5) Zone of allotropic transformation of quartz.
(6) Final cooling zone (number of closed modules
and in use).

The dimensions of the furnace module may be varied at our discretion, within reasonable limits that
Allow the modelling of the problem not to be seriously affected. With these variations we can study, for example, the height of the oven channel for optimal energy use.
The width of the channel is a factor already more studied by the manufacturers of
ovens, but for example the length of each module is also an important parameter, since it influences other
Considerations such as the arrangement of the burners in this new module.
It is also possible to analyze the two types of rollers most used in this type of ovens. Regarding the burners, in addition to being able to enter the desired number, with its corresponding operating index, the diameter of the outlet nozzle of the injectors of each burner can be varied. Logically, it can be intuited that a nozzle diameter
Higher velocity causes a lower jet of flue gas leaving each module, and therefore the
Oven sees the transmission of heat to the pasta disadvantaged.
This effect can be clearly seen by changing this diameter within limits.

Finally, within the program you can vary both the outside temperature of the house and the relative humidity of the same, to see what effect these variations have on the final temperature values of the pasta to be cooked.
Normally, this effect will not be very appreciable, since the variations of these values will be little comparable with the temperature values in which we move.
In addition to the purely design parameters of the monolayer furnace, the furnace can study the effect of other values that have been introduced by default in it: as an example one could study the variation of the
Surface and thermal properties of the materials usedin its construction: conductivities, emissivities, etc. Other parameters could be the
arrangement and number of nozzles in the cooling zone, spacing between these tubes, etc.
Theoverall results of gas consumption and specific consumption per kg of pasta to be cooked are in line with

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The data provided with the Castellón industry, for identical curves of each type of pasta and simulated in the monolayer oven.

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