# TEMPERATURE DISTRIBUTION INSIDE A CERAMIC TILE DURING INDUSTRIAL FIRING

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## ABSTRACT

*With a view to estimating ceramic tile surface and inner temperature during firing, a model has been developed that accounts for heat transfer phenomena by convection and radiation from the kiln to the tile surface, and heat transmission by conduction inside the tile. The thermal parameters required for the calculation have been determined by laboratory tests. These tests have included measurement of thermal conductivity and chemical reaction kinetics.*

*The model has been verified by temperature measurements at the tile surface, made with a temperature probe. For this, several K-type thermocouples were fixed to the tile top and bottom surfaces, recording tile surface temperature during firing as the tile advanced through the kiln. These tests have provided a more accurate estimation of the heat transmission mechanisms in the kiln.*

*The results indicate that the rollers act as a very important barrier to heat transmission in the kiln. It has been shown that very significant thermal differences can exist between the tile surface and the kiln thermocouples. In addition, the calculations show that, at times, the tile surface temperature values do not match what might intuitively be expected; in particular, the difference in temperature between the tile top and bottom surfaces does not depend in a simple way on the thermal difference between the top and bottom channels of the kiln.*

## 1. INTRODUCTION

The firing of ceramic tiles is one of the most important stages in the ceramic process, and provides the product with its mechanical properties and final aesthetic characteristics. Tile properties and characteristics depend, therefore, on the kiln temperature curve. This curve is usually not known, since the only available information is that supplied by the kiln thermocouples. Tile temperature and kiln temperature can differ for numerous reasons: temperature gradients in the kiln, thermal delay of the piece in relation to the thermal curve of the kiln, heat absorption as a result of chemical reactions, screening by the rollers, etc.

A thorough understanding of the evolution of temperature at the tile surface would, in addition to facilitating better control of firing, facilitate the extrapolation of the results of firings in a laboratory kiln to industrial firings.

Although studies have been conducted aimed at calculating, theoretically, tile temperature during firing[1,2,3,4] or at determining this temperature experimentally[5], few studies combine the theoretical thermal calculation with its experimental verification.

## 2. THEORETICAL MODEL

### 2.1. HEAT TRANSMISSION FROM THE KILN TO THE TILE SURFACE

In order to be able to calculate the tile surface temperature from kiln gas temperature, it is necessary to know the heat transfer coefficients in the kiln. Inside a kiln, heat is transferred basically to the tile by two mechanisms: convection and radiation. The heat flow density ($q_T$, in W/m$^2$) that reaches the tile is the sum of the heat that it receives by convection ($q_C$) and radiation ($q_R$):

$$q_T = q_C + q_R$$

where:

$$q_C = h_C(T_h - T_S)$$
$$q_R = h_R(T_h - T_S)$$

$T_h$ is kiln temperature, $T_S$ is tile surface temperature, and $h_C$ and $h_R$ are the coefficients of heat transfer by convection and radiation, respectively. According to the literature surveyed[6], $h_C$ can be written as:

where $h_{C0}$ and $h_{C1}$ are two empirical coefficients, and $v_A$ is the gas circulation

$$h_C = h_{C0} + h_{C1}\sqrt{\frac{v_A}{T_h}}$$

velocity in the kiln.

On the other hand, the coefficient of heat transmission by radiation can be written as:

$$h_R = 4\sigma\varepsilon_M T_h^3$$

*Equation 1*

where $\sigma$ is the Stefan-Boltzmann constant and $\varepsilon_M$ is the resulting emissivity.

Figure 1 shows the coefficients of heat transmission by convection and radiation versus temperature.

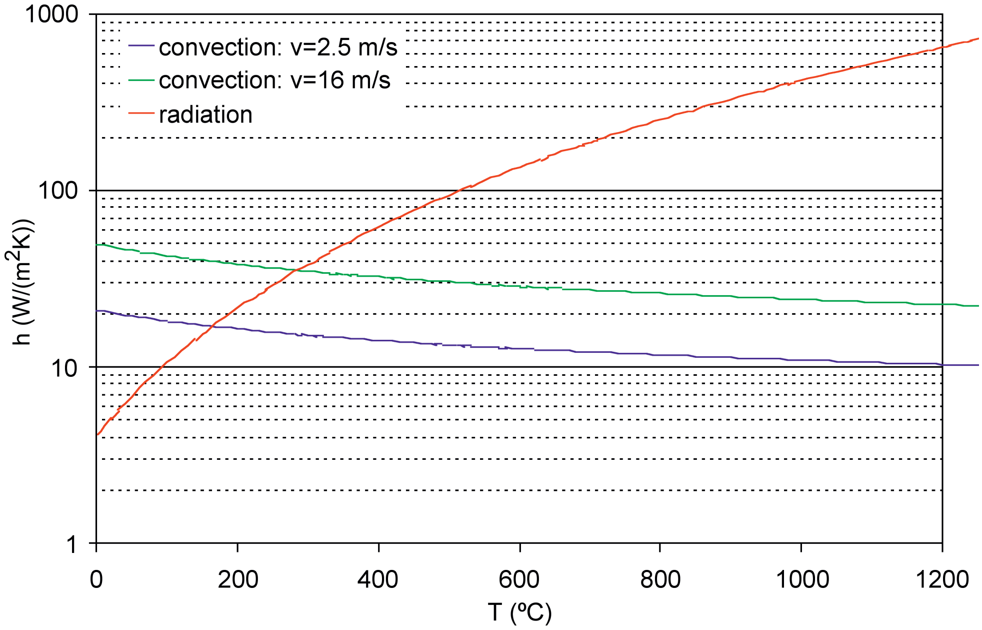


*Figure 1. Coefficients of heat transmission by convection and radiation versus temperature.*

The coefficient of heat transmission by convection depends on the gas circulation velocity, which is difficult to determine experimentally. For this reason, two limit gas circulation velocities have been estimated and the limits have been calculated between which $h_C$ might be expected to vary.

It can be observed that the fundamental heat transmission mechanism is radiation. Therefore, the contribution of convection need not be calculated with great accuracy. There are only two cases in which convection could be important: low temperatures (below 400 ºC) or very high gas velocities (fast cooling)[7].

To perform the heat transmission calculations, a number of additional assumptions have been made:

- The coefficient of heat transmission by convection was permitted to differ in heating and in cooling (being much larger in cooling). This is because the velocity (and angle of incidence) of the gases in cooling could greatly favour heat transmission.

- The 'resulting emissivity' ($\varepsilon_M$), which takes into account heat transmission by radiation, might be different in heating and in cooling. The reason could be the different nature of the gases in heating and cooling ($CO_2$ strongly absorbs radiation), or the fact of assuming that the gas temperature coincided with that of the kiln walls.
- Rollers have a marked effect on heat transmission by convection and radiation. Studies in the literature report that, especially in the case of ceramic rollers, these have a heat flow-resistant role. Unfortunately, this resistance cannot be readily estimated on the basis of purely theoretical considerations[7, 8]. Therefore, it was decided to determine a value from the fit of the experimental data.

## 2.2. HEAT TRANSMISSION INSIDE THE TILE

The equation for heat transmission in a non-steady state inside the tile takes the form:

$$\rho c_p \frac{\partial T}{\partial t} = k\nabla^2 T + G_E$$

*Equation 2*

where:

| | |
|---|---|
| T: | temperature in a point of the tile at a given moment (ºC) |
| t: | time (s) |
| $\rho$: | density (kg/m$^3$) |
| $c_p$: | heat capacity (J/(kgK)) |
| k: | thermal conductivity (W/(mK)) |
| $G_E$: | heat generation (W/m$^3$) |

The term 'heat generation' corresponds to the heat absorbed or released by chemical reactions. Therefore, in the fired material it is zero. In the green material, the clay dehydroxylation reactions and calcium and magnesium carbonate decomposition are important.

## 2.3. BOUNDARY CONDITION AND SOLUTION OF THE MODEL

To solve equation 2 it is necessary to know tile surface temperature or kiln temperature at every moment (this is what is known as the boundary condition). In the first case the calculation is more accurate, as it does not require the use of heat transmission coefficients. However, tile surface temperature is usually unavailable. It was decided, therefore, to use kiln temperature as the boundary condition. This then yielded the tile surface temperature by calculation (and not as an a priori known datum).

Unfortunately, kiln temperature is only known at the points fitted with thermocouples; in the initial heating zone (below 600 ºC) and in the cooling zone, in particular, this information is very fragmentary. At some points the temperature is available in the top zone, but not in the bottom zone. For all these reasons, it was necessary 'to complete' the temperature curve in the kiln.

Having posited all the equations and assumptions, we needed to solve the equations numerically. For this we used the method of finite differences, using a program developed in C++ [4,9].

## 3. EXPERIMENTAL DETERMINATION OF TILE TEMPERATURE

### 3.1. MEASUREMENT OF TILE THERMAL PROPERTIES IN THE LABORATORY

To quantify the thermal behaviour of the material, a number of cylindrical test pieces were prepared and placed inside a kiln (figure 2). The test pieces had a central orifice into which a thermocouple was inserted. In this type of test two successive heat treatments were applied: in the first cycle the piece was initially green, whereas in the second the piece was initially partly or completely fired (depending on the peak temperature in the first cycle). If the material underwent no transformations during firing, the evolution of temperature in the centre of the test piece would be the same in both cycles. In contrast, if the piece underwent physico-chemical transformations accompanied by absorption or release of heat, the temperature curve in the centre could differ.

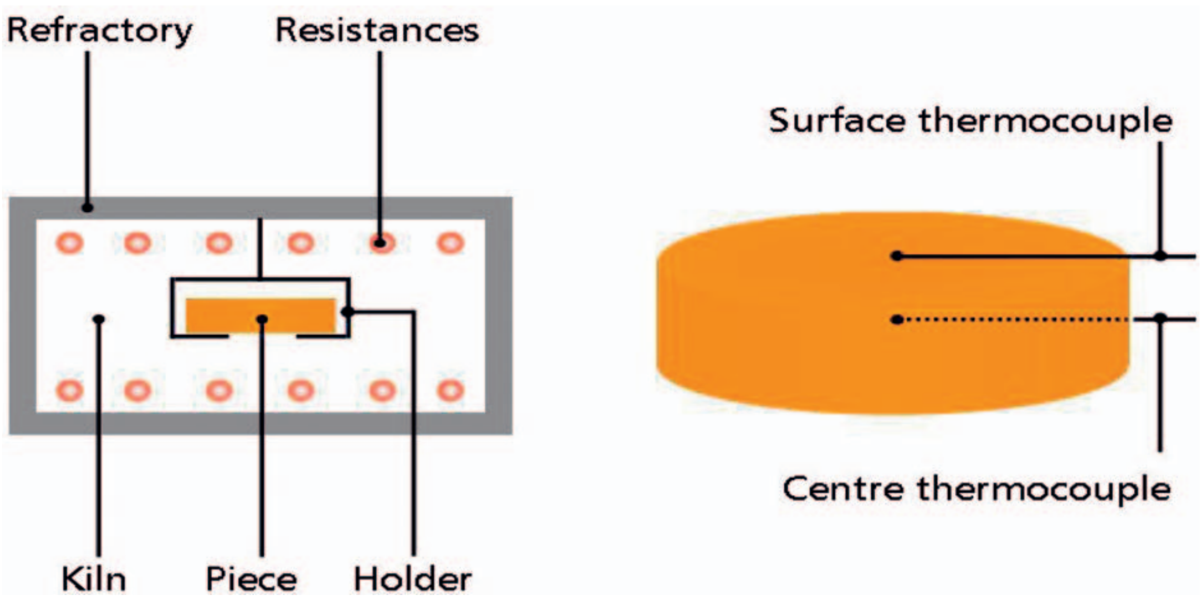


*Figure 2. Set-up used to measure the thermal properties.*

Figure 3 depicts, in blue, the evolution of temperature in the centre of the test piece as a function of time, for different peak temperatures. The series in red have been obtained theoretically from the heat transmission equation (equation 2), determining, with this, the thermal properties of the material (including the chemical reactions).

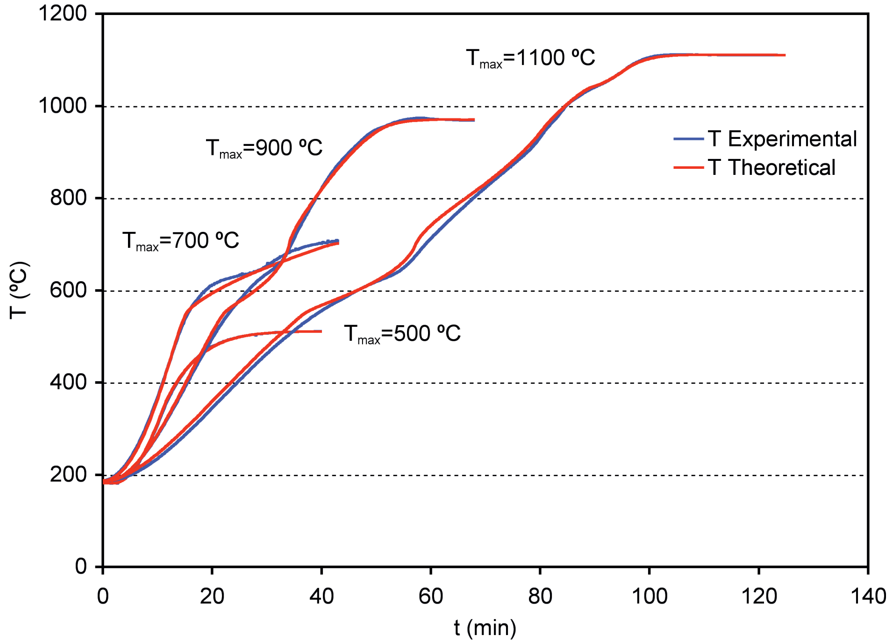


*Figure 3. Evolution of temperature in the centre of the tile.*
*Comparison of experimental and theoretical results.*

## 3.2. DESCRIPTION OF THE INDUSTRIAL SET-UP

The experimental objective was the measurement of the tile top and bottom surface temperature during firing in a single-deck roller kiln. For this, a Datapaq temperature probe was used. The probe consists basically of three elements: a data recorder, a heat barrier and a group of thermocouples that can be set in contact with the tile or with the kiln gases.

The data recorder reads and stores the temperature measured by the thermocouples. It runs on batteries, and is able to withstand a maximum temperature of 110 ºC. The thermal insulation of the recorder consists of a heat barrier made up of an external ceramic fibre layer, and internal stainless steel housing with a water jacket. The thermocouples used were of the K type, 1.5 mm in diameter, which enabled fixing these easily to the surface of the tiles.

The experiment was conducted on white wall tile bodies of 30 x 60 cm. Six thermocouples were placed on the tile: three at the bottom and three at the top surface. Figure 4 schematically illustrates the arrangement of the six thermocouples.

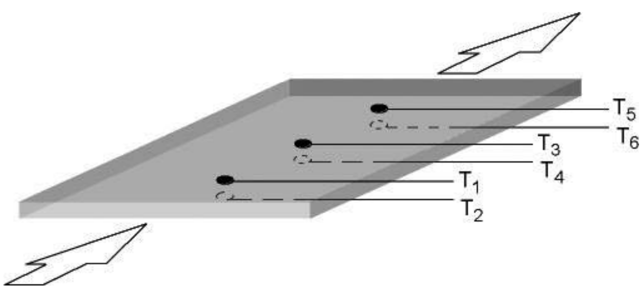


*Figure 4. Position of the thermocouples on the tile surface.*

The sensors were fixed to the tile with a high temperature-resistant wire, which passed through the tile via two previously made holes. Figure 5 shows a picture of the sensorised tile. This tile was set in the centre zone of the kiln, and the surrounding deck of tiles was maintained in order not to disturb the temperature curve by the presence of gaps.

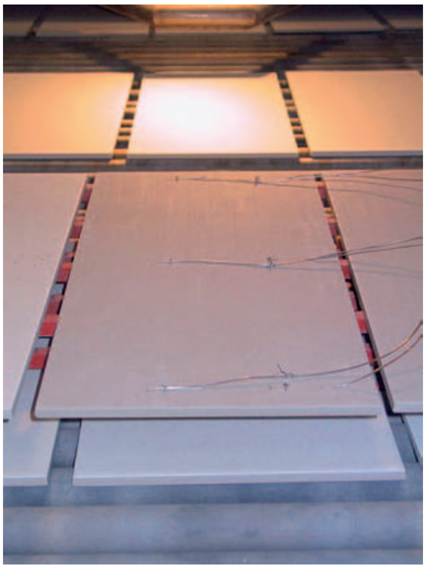

*Figure 5. Picture of the tile with the six fitted thermocouples.*

When the thermocouples had been fitted to the tile, the heat barrier was prepared, and the thermocouples were connected to the data logging system. The entire assembly was placed in the kiln, as if it were just another tile. Figure 6 shows a photograph of the assembly consisting of the sensorised tile and the Datapaq probe taken moments before the assembly entered the kiln.

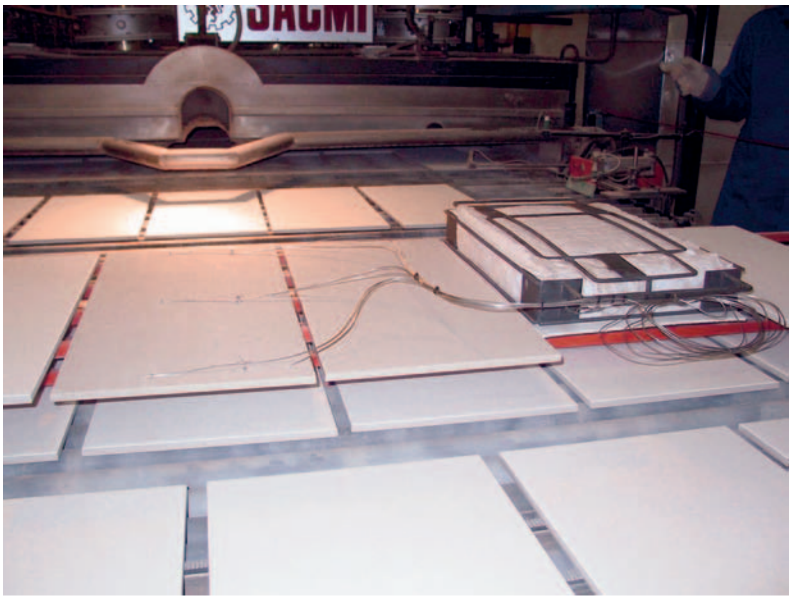

*Figure 6. Photograph of the sensorised tile–Datapaq probe assembly before the assembly entered the kiln.*

### 3.3 RESULTS

First, a comparative analysis was made of the temperature provided by the kiln control thermocouples and the temperature recorded at the tile surface. Figure 7 shows the temperature of the kiln thermocouples in the top and bottom zones of the kiln (plotted, respectively, as Tg Top and Tg Bot), as well as the mean temperature obtained at the tile top (Ts Top) and bottom (Ts Bot) surfaces.

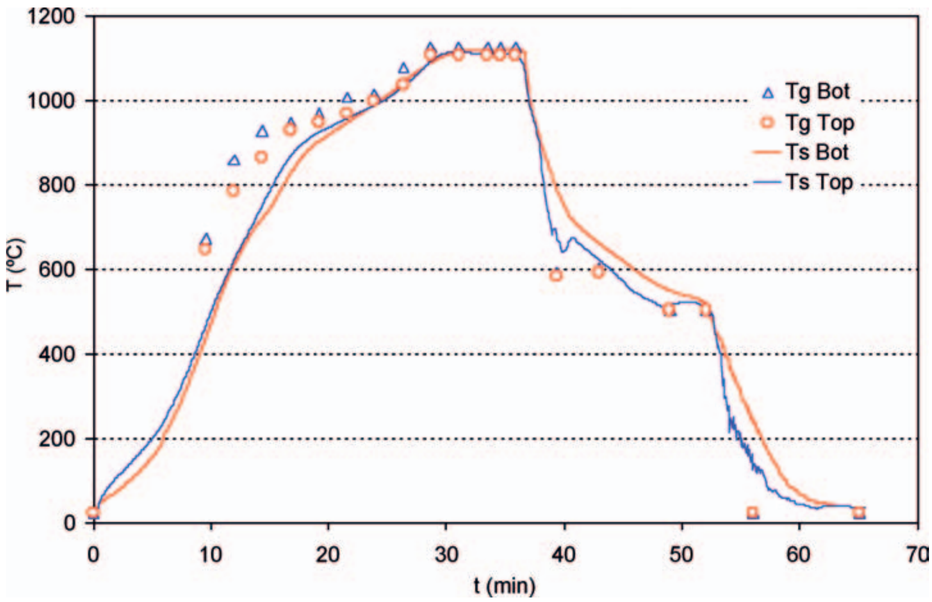


*Figure 7. Kiln gas temperature ($T_g$: circles (top zone) and triangles (bottom zone)) and tile surface temperature ($T_s$: solid lines).*

In general, significant differences can be observed between gas and tile temperatures: the differences in the stretches of firing cycle with a high heating or cooling rate are especially pronounced.

During preheating, the thermal delay of the tile in regard to gas temperature reaches 200 ºC, and diminishes as the heating rate decreases, until the temperatures in the firing zone finally equalise. In the cooling zone, little information on gas temperature is available, since there are few thermocouples. Forty minutes into the cycle, when the gases have cooled down to 600 ºC, the tile surfaces are observed to be noticeably hotter than the gases.

The temperature of the kiln gases in the bottom zone is greater than in the top zone throughout the heating. However, in some periods of the thermal cycle, the tile surface exhibits the opposite tendency, with a hotter top than bottom surface.

Figure 8 plots the mean temperature recorded by the six thermocouples, as well as the difference between the top and bottom temperature in three regions of the tile: front ($T_5$-$T_6$), centre ($T_3$-$T_4$) and back ($T_1$-$T_2$) (according to the tile direction of advance in the kiln).

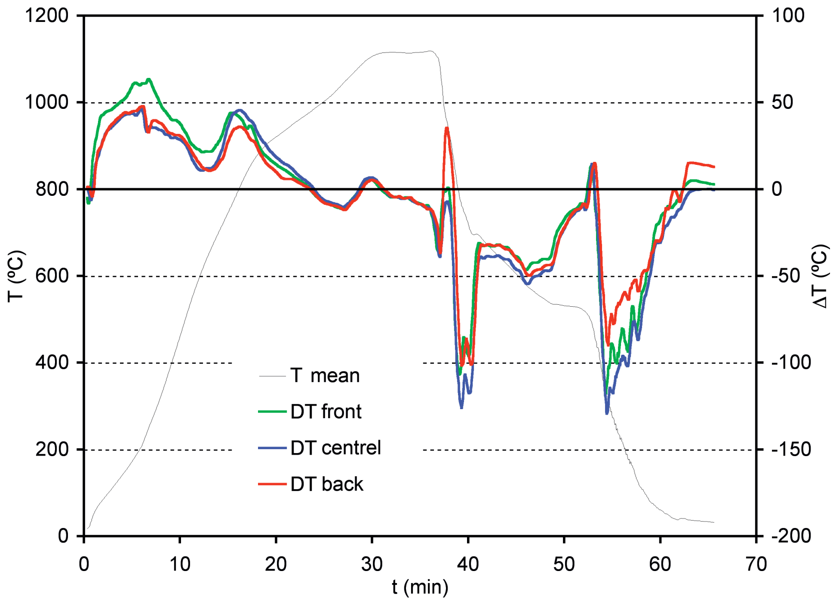


*Figure 8. Mean temperature, and difference in temperature between tile top and bottom surfaces in three regions of the tile.*

The temperature differences between the top and bottom surfaces are positive during heating (the top surface is hotter than the bottom surface). The opposite occurs during cooling.

The greatest temperature differences between the two tile surfaces occur in the stretches in which the heating or cooling rate is greatest. The differences found during cooling are particularly high, and reach up to 100 ºC.

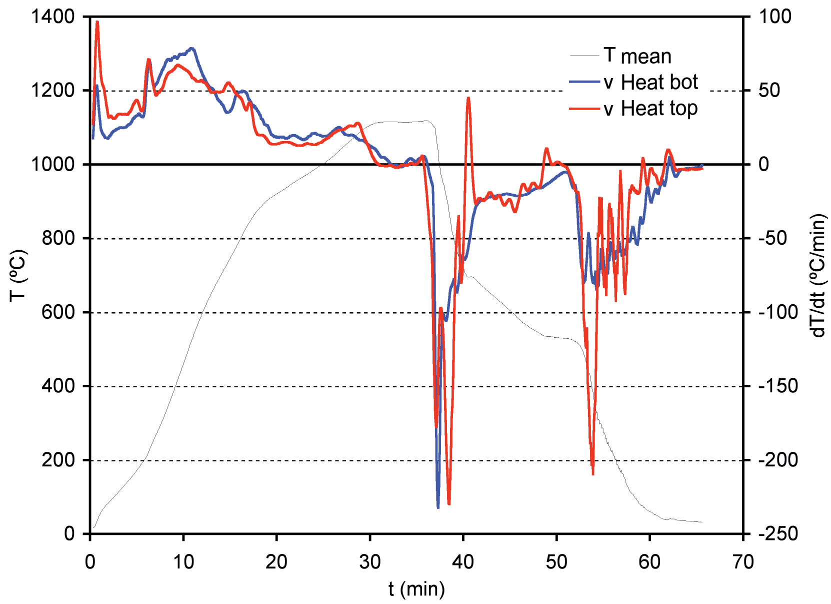


*Figure 9. Heating and cooling rates at the tile surfaces.*

Together with the temperature differences, it is interesting to analyse the heating and cooling rate in the tile (figure 9). It can be observed that during heating the rate at which temperature changes in the tile is similar in the top and bottom surfaces, and is about 50 ºC/min. However, during cooling this reaches -200 ºC/min. In addition, there are important differences in the cooling rate of both surfaces, possibly due to the effect of the rollers.

In the final cooling phase, temperature swings are detected (especially in the top tile surface). These swings may be due to the presence of cooling tubes in the kiln, which cause cold air to impinge directly on the tile surface.

## 4. APPLICATION OF THE MODEL

### 4.1. ESTIMATION OF TILE SURFACE TEMPERATURE

Applying all the foregoing assumptions and simplifications it is possible to calculate tile surface (and inner) temperature over time. Figure 10 plots:

- The temperature of the kiln thermocouples, as well as some temperatures measured by thermocouples in the cooling zone (in which, as mentioned, the number of thermocouples is very scarce).
- The temperature measured with the Datapaq probe.
- The temperature calculated theoretically from the estimated heat transmission coefficients.

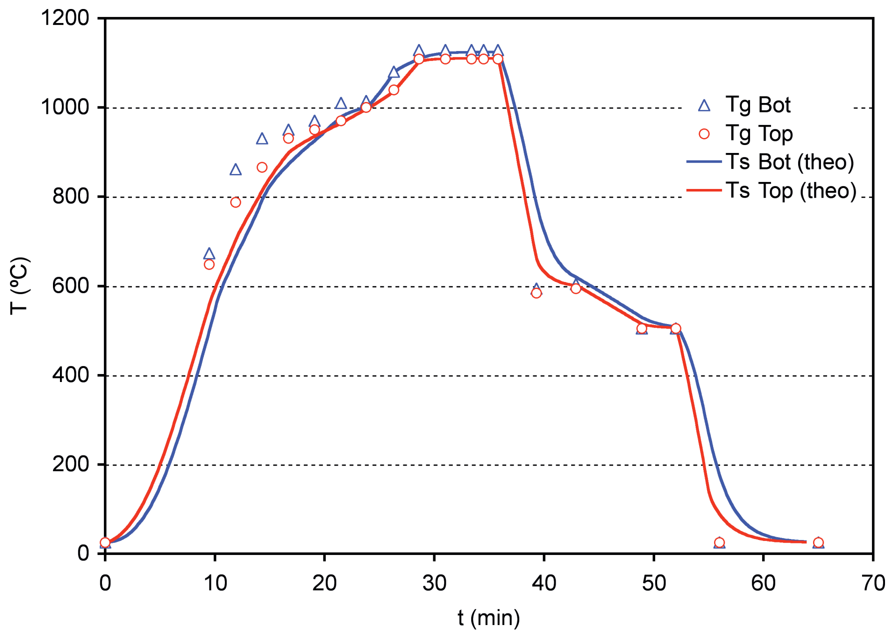


*Figure 10. Temperature recorded by the thermocouples (points) and temperature curve of the tile surface calculated from the model developed.*

Comparison of this graph with figure 7 reveals good agreement, especially in the initial cooling zone, a zone in which the kiln thermocouples contribute little information.

Figure 11 shows the difference in temperature between the top and bottom part of the tile, and the value of this difference, estimated from the theoretical equations and from the temperature of the kiln thermocouples. Generally speaking, the fit is observed to be good. In particular, the theoretical results enable explaining that the tile top surface temperature is higher, even though the gases are hotter in the bottom zone. The greatest discrepancies are found in:

- The initial moments (in this zone there are few thermocouples and the estimation of gas temperature may not be correct).
- At the moment t≅25 min, at which the theory yields a temperature difference of about -40 °C, and the value obtained experimentally is about 10 °C. Observation of the temperatures of the thermocouples shown in figure 11 indicates that the bottom/top gas temperature difference is very high (80ºC). After performing these calculations it was verified that the problem lay in the bottom thermocouple temperature reading, which was anomalously high because the hot gases of the burner impinged directly on it.

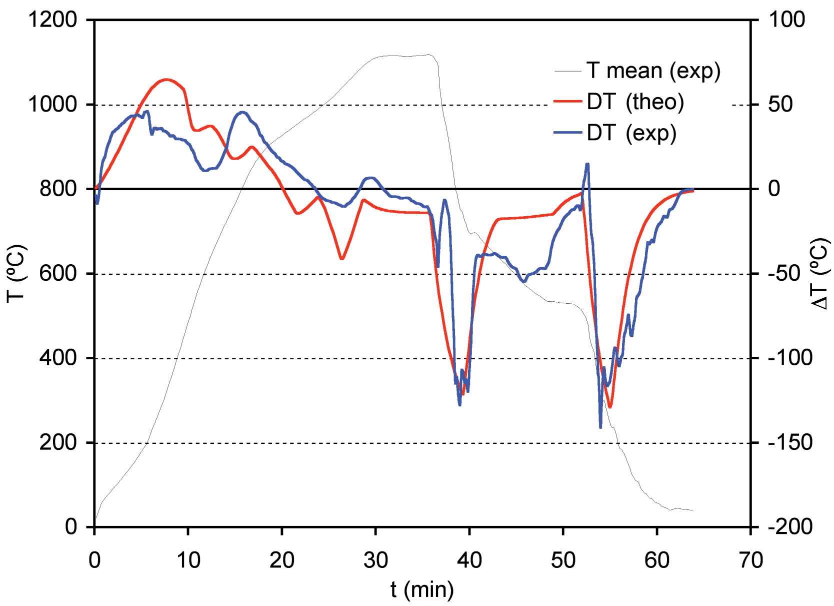


*Figure 11. Temperature difference between the top and bottom surfaces (T top - T bot) of the tile during industrial firing. Comparison of the theoretical and experimental values.*

## 4.2. INNER TEMPERATURE PROFILES

In addition to establishing the temperature of the tile surface, the calculation made enables estimating the temperature at any point inside the tile. This temperature is important because it influences:

- The reactions that unfold inside the tile (combustion of organic matter and carbonate decomposition).
- Strains originating during heating.

- Stresses within the tile (cracks and explosions during heating, or tile breakage in cooling by the β→α quartz transition).
- Residual stresses in the tiles at the kiln exit.

Figure 12 displays the difference in temperature between the tile centre, and top and bottom surfaces throughout the firing cycle.

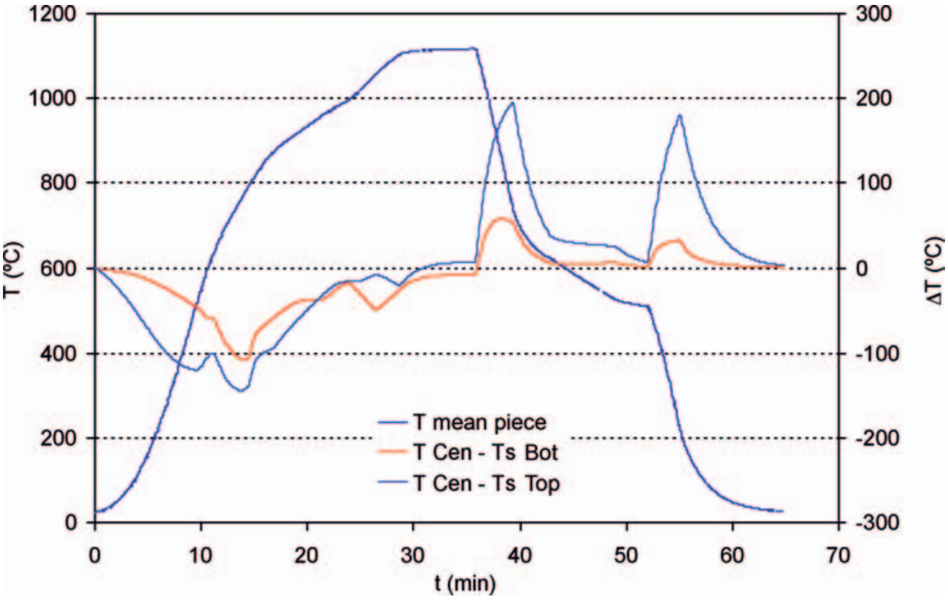


*Figure 12. Temperature difference between the tile centre and surface.*

It can be observed that throughout the heating, the centre is colder than the surface (negative temperature difference). This difference can reach values exceeding 100 ºC, in absolute terms.

In cooling, two zones appear in which the temperature difference practically reaches 200 ºC. The centre–surface temperature difference is greater in the top face of the tile because the cooling is more effective through this surface, possibly because there are no rollers to prevent heat transfer.

In general, the temperature difference between the tile interior and the surface ($\Delta T_C$) depends on several factors, such as:

- Heating or cooling rate: the higher the rate, the greater will also be $\Delta T_C$.
- Thermal properties of the material: low thermal conductivities (high porosity) cause $\Delta T_C$ to be high.
- Chemical reactions in the body: dehydroxylation reactions of the clay material and carbonate decomposition absorb heat and, therefore, 'cool' the centre of the tile.
- Thickness of the tile: as heat transmission takes place by conduction, tile thickness plays a very important role, causing the temperature difference to increase with thickness.

The simulation performed enables quantifying all the foregoing factors.

## 5. CONCLUSIONS

Temperature measurements have been carried out inside a kiln, at the tile top and bottom surfaces. These show:

- There are important differences between the temperature of the kiln gases and that of the tiles (200 ºC), particularly when the heating or cooling rate is high.
- The heating rate is incidentally high (70 ºC/min), but the cooling rate is much greater (-220 ºC). This could generate very important stresses.
- There are significant differences in temperature between the tile top and bottom surfaces (over 100 ºC).
- Sometimes the thermal differences between the tile top and bottom surfaces have the opposite sign to those of the gases.

A model has been developed based on heat transmission by convection and radiation from the kiln to the tile surface, and by conduction inside the tile. The model enables establishing:

- Tile surface temperature: the fit with the experimental data is good.
- The difference in temperature between the top and bottom tile surfaces, as well as the thermal difference between the tile surface and centre.
- The effect of the rollers as a heat transmission-screening element in the kiln.

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