ESTIMATION OF THE INFLUENCE OF THE CERAMIC COMPOSITION ON THERMAL ENERGY CONSUMPTION

A. Escrig, J. García-Ten, A. Mezquita, S. Ferrer, V. Cantavella[1],

E. Monfort

Instituto de Tecnología Cerámica (ITC). Asociación de Investigación de las Industrias Cerámicas (AICE)

Universitat Jaume I. Castellón. Spain.

1. ABSTRACT

Ceramics manufacture requires a great thermal energy input for the drying and firing operations. This energy consumption is largely conditioned by the technology used, both in regard to the facilities used and in aspects relating to their optimisation (thermal insulation, heat recovery, operating conditions, etc.).

However, the nature of the ceramic composition also influences the thermal energy consumption associated with composition processing. This is particularly the case in the firing operation, which accounts for the largest part of total thermal energy consumption, this being directly and indirectly affected by the ceramic composition.

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[1] Currently at Grupo Esmalglass – Itaca.

The content in compositional components that undergo endothermic or exothermic transformation during firing directly affects energy consumption in firing. In addition, the ceramic composition determines, at least partly, the firing cycle (peak temperature, cycle duration, decomposition stages, etc.) to which the ceramic pieces must be subjected to obtain the desired specifications. Therefore, modifying the composition can entail a variation in the firing cycle, which can in turn affect kiln energy consumption.

It is difficult to quantify the above effects experimentally, as this would involve firing a sufficient production volume for each test condition, in order to have steady, stable conditions in every case. In addition, to assure analogous firing conditions (e.g. in terms of excess of air), the kiln would need to be regulated in each case.

This study used a theoretical approach to estimate the influence of the ceramic composition on thermal energy consumption in ceramic tile firing. The estimation was performed using a theoretical model simulating energy transfer in single-deck roller kilns for firing ceramic tiles.

The mathematical model of energy transfer used is based on the zone method. In this method, the kiln is divided into surface zones and gas zones, which are sufficiently small to be deemed isothermal, and an energy balance is drawn up for each of these. Solving the energy balance yields an estimation of the temperatures in all system zones. The developed computer program allows the problem to be addressed in reverse, i.e. a given firing curve can be specified, which then yields kiln energy consumption.

The kiln simulation program enabled the influence, in firing, of factors relating to the ceramic composition (such as carbonate content, peak firing temperature, and cycle duration) on thermal energy consumption to be estimated.

2. INTRODUCTION

The most recent study of energy consumptions in the ceramic industry in Castellón was performed in 2008 [1, 2]. The study highlighted the sector's greater thermal energy demand compared to its electric power demand ($50\cdot10^9$ MJ compared to $4.3\cdot10^9$ MJ). The firing stage accounted for the most important part of all thermal energy consumption, namely 50%.

At present, fast single firing in single-deck roller kilns is widely used in the Spanish ceramic tile sector. Consequently, the variability in energy consumptions in ceramic tile firing in the Spanish sector does not stem from the use of different technologies, but rather from different kiln operating conditions in relation to the degree of kiln optimisation (thermal insulation, heat recovery, etc.) and to factors relating to the product being manufactured.

Indeed, the sector study revealed significant differences in the specific consumption data recorded for each type of ceramic tile. According to this study, red-body stoneware tile products required the lowest energy input per unit mass of fired product compared to that of earthenware wall tiles and porcelain tile (Figure 1a). However, when the consumptions were expressed per functional unit (m^2), the lower specific weight of fired wall tiles (kg m^{-2}) largely offset their greater consumption per unit mass. In these terms, porcelain tile was the product that evidenced a greater energy demand (Figure 1b) [1, 2].

3. THEORETICAL MODEL

3.1. GENERAL APPROACH

Practically all kilns used in the Spanish ceramic tile manufacturing sector are single-deck roller kilns fuelled by natural gas, which reach maximum temperatures of about 1100–1200 ºC. Under these conditions, radiation is the predominant energy transfer mechanism. In addition, the presence of carbon dioxide (CO_2) and water vapour (H_2O) in the combustion gases (generated in natural gas combustion, as well as in the decomposition of ceramic composition constituents) causes these to participate in the absorption and emission of thermal radiation.

Thermal radiation exchange in the presence of an absorbing gas is a complex phenomenon. Radiant energy transfer under these circumstances is described by an integral–differential equation [3]. This is because, when an energy balance is drawn up of an infinitesimal control volume, this can emit and receive thermal radiation from every direction.

The method chosen to solve the radiant energy conservation equation in a roller kiln was the zone method [4–7]. In this method, the system is broken down into a series of sufficiently small volumes and surfaces – *zones* – to be deemed isothermal. The zone method allows the radiative flows between these zones to be calculated and other energy flows, such as the enthalpy or convective exchange flows, to be readily incorporated.

The first step in applying the zone method consisted of breaking the kiln down into zones. As the main dimensional characteristic of single-deck roller kilns is their length (compared to their other dimensions), the kiln was divided into a series of longitudinal sectors (Figure 2a) made up of a set of elements (Figure 2b) corresponding to the zones in the zone method.

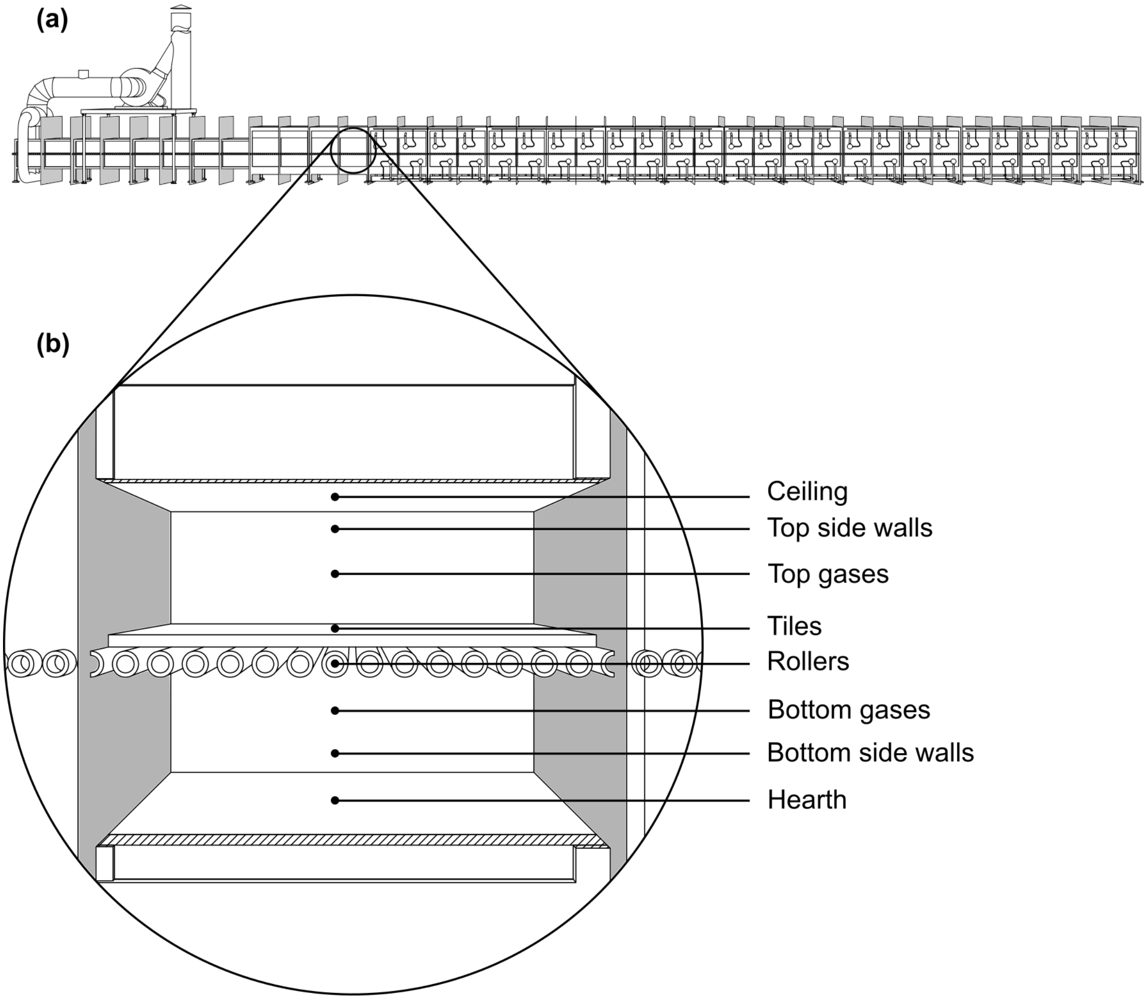

Figure 2. *Zonal division of the kiln.*

Once the system had been divided into zones, the thermal radiation exchange between the zones could be rigorously calculated. Three sets of exchange areas were successively calculated: the direct exchange areas, the total exchange areas, and the directed flux areas, which gradually incorporated the radiant properties of the system elements. The greatest calculation effort was required in the assessment of the direct exchange areas, because this involved calculation of $O(m \cdot m+m \cdot n+n \cdot n)$ integrals of order 4 to 6, where m is the number of surface zones and n is the number of gas zones.

On formulating the energy balances for each zone, beside the radiative exchange, other energy flows, such as those associated with the materials flows or heat conduction through the walls, needed to be incorporated. In this study, particular attention was paid to the treatment used for the tiles, which is briefly described in the following section.

3.2. ENERGY FLOWS ASSOCIATED WITH THE CERAMIC COMPOSITION

The enthalpy flows associated with the tiles that left a certain zone *i* were expressed in the following form:

$$m\left(1-\sum_{k=0}^{q}\xi_k(T_i)w_k\right)\bar{c}_{pb}\left(T_i-T_{\mathrm{ref}}\right)+m\sum_{k=0}^{q}\left(\xi_k(T_{i-1})-\xi_k(T_i)\right)w_k\Delta H_k^0(T_i) \qquad \textbf{(1)}$$

where:

m is the mass flow rate of unfired tiles,

T_i is tile temperature in zone *i*,

T_{ref} is the reference temperature,

$\bar{c}_{pb}$ is the average heat capacity of the tiles,

ξ_k is the degree of advance of the *k*–th chemical reaction,

w_k is the mass fraction of the key component of the *k*–th chemical reaction,

ΔH_k^0 is the specific enthalpy (J kg^{-1}) of the decomposition products of the *k*–th chemical reaction relating to the key component.

Note that, for the first term of Equation (1) to be meaningful, the gaseous decomposition products of the different chemical reactions must be chosen as the respective key components. The second term, on the other hand, takes into account the incorporation of these products into the gas stream.

The degree of advance of the different chemical reactions was considered to take the form [8, 9]:

$$!_{k}=\left(3\Theta_k^2-2\Theta_k^3\right)\left(\Upsilon(\Theta_k)-\Upsilon(\Theta_k-1)\right)+\Upsilon(\Theta_k-1) \qquad \textbf{(2)}$$

where $\Upsilon(\bullet)$ is the Heaviside function and:

$$\Theta_k=\frac{T_i-T_{k*}}{T_k^*-T_{k*}} \qquad \textbf{(3)}$$

in which T_{k*} and T_k^* are the start and end temperatures, respectively, of the chemical reaction *k*.

The energy released in each zone was calculated from:

$$m\sum_{k=0}^{q}\left(\xi_k(T_{i-1})-\xi_k(T_i)\right)w_k\Delta H_{r,k}^0 \qquad \textbf{(4)}$$

where $\Delta H_{r,k}^0$ is the heat of reaction of the *k*–th chemical reaction at the reference temperature.

The main reactions of thermal relevance that take place during ceramic tile firing are carbonate decomposition and clay mineral dehydroxylation, both of which are endothermic [8, 10]. The products released are CO_2 and H_2O, which are released in significant quantities with regard to the associated enthalpy flows as well as to the modification of the radiating properties of the combustion gases. For example, in an earthenware wall tile composition (13% carbonate content and 10% loss on ignition) at the average consumption indicated in Figure 1, the CO_2 and H_2O released by the chemical reactions would account for about 30% of all the CO_2 and H_2O in the combustion gases.

4. VALIDATION OF THE MODEL

With a view to validating the prediction capability of the developed model, a series of experiments were performed in three industrial kilns where different types of products were processed. In these experiments, the kiln operating conditions were recorded, using the usual respective operating conditions. Based on this information and the structural characteristics of the kilns, the temperatures in the different zones were calculated and compared with the experimental data. In general, differences of less than 5% between the temperatures calculated from the model and those recorded in the experiments were obtained.

For reasons of space, the specific data are not reported in this paper, as the tested experimental conditions, kiln characteristics, etc., need to be described in detail However, it is intended to set out this information in a future publication.

5. CASE STUDY

A hypothetical roller kiln with 50 modules was selected, 30 of which were in the preheating and firing zones. The kiln was equipped with burner rings from module 13 to module 30. Each ring grouped the burners above or below the roller plane of two modules, for which a single temperature setting was specified. For the sake of simplicity, the temperature settings of the top and bottom ring were assumed to coincide.

A base firing curve was defined on which to perform the corresponding modifications. The curve shape is shown in Figure 3. Three characteristic parameters of this curve were defined: total cycle duration (τ), residence time at peak temperature (τ_m), and peak firing temperature (T_m). The other firing curve characteristics, such as the existence of a decomposition step, with a different heating rate, between 800 and 900 ºC, are illustrated schematically in Figure 3. Just as in the industrial situation, the firing curve was only specified at particular positions, through a series of temperatures settings for each burner ring.

The studied composition was an earthenware wall tile composition with 13 wt% carbonate content (in the form of $CaCO_3$) and 10% loss on ignition (assumed to be solely due to CO_2 and H_2O release in the reactions mentioned above).

A further aspect to be specified was the excess air. As reference conditions, the burners were considered to contribute, as a whole, 30% excess air. However, the kiln was regulated such that the air pressure provided in each ring was constant throughout the kiln.

Using this base case, a series of simulations were performed to estimate the following:

- Influence of carbonate content
- Influence of peak firing temperature
- Influence of cycle duration

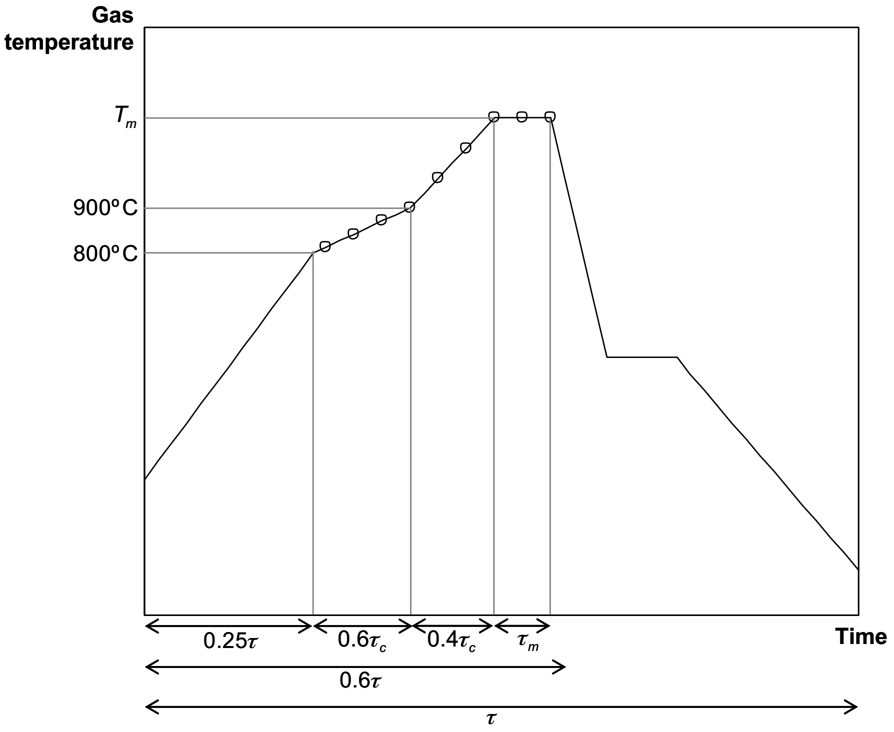

Figure 3. *Firing curve. The setting values are represented by means of circles.*

6. RESULTS AND DISCUSSION

A hypothetical partial reduction of the carbonate content in the composition by another raw material that contributed a similar behaviour in firing, without significant endothermic transformations, was studied. The use of wollastonite was proposed in this sense [11].

Figure 4 shows the calculated variation in kiln energy consumption on modifying the carbonate content in the composition. To facilitate the comparison with Figure1, in this section the energy consumptions are expressed per unit fired product mass and they have been calculated from the higher heating value. To express the consumptions by kg of fired product, the partial replacement of carbonates with another hypothetical raw material that did undergo outgassing would entail a reduction in energy consumption, owing to the greater specific weight of the product. In order to be able to distinguish this effect, in Figure 4 the resulting reduction is shown by an additional line.

The calculation was performed in two ways: keeping the excess air constant and keeping the supplied air volume constant under the reference conditions. As may be observed, when carbonate content decreased, energy consumption also decreased, particularly when the increase in excess air stemming from lower kiln energy consumption was corrected.

According to the calculations made, total removal of the carbonates could entail a 13% reduction in energy consumption under the conditions studied (subtracting the effect of the greater specific weight of the material). In addition, eliminating the carbonates could make the decomposition stage identified in Figure 3 unnecessary, possibly leading to a shorter cycle which, as will be seen below, could also have a positive effect on energy consumption.

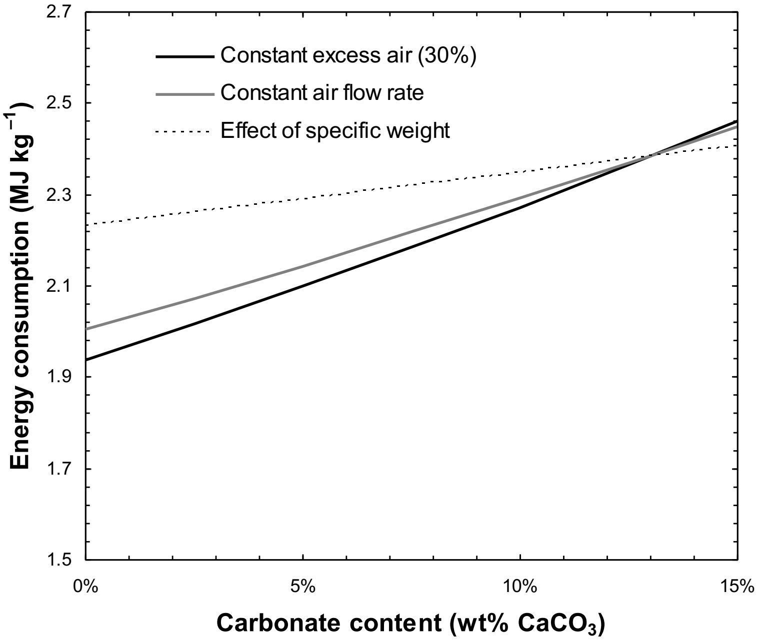

Figure 4. *Variation of energy consumption with the carbonate content.*

The effect of modifying peak firing temperature (holding the other cycle characteristics) is shown in Figure 5. Within the margins of variation of the studied peak temperature, the variations relating to energy consumption were moderate. As was to be expected, consumption decreased with peak firing temperature, but a reduction of 100 ºC would only modify consumption by 6.5%.

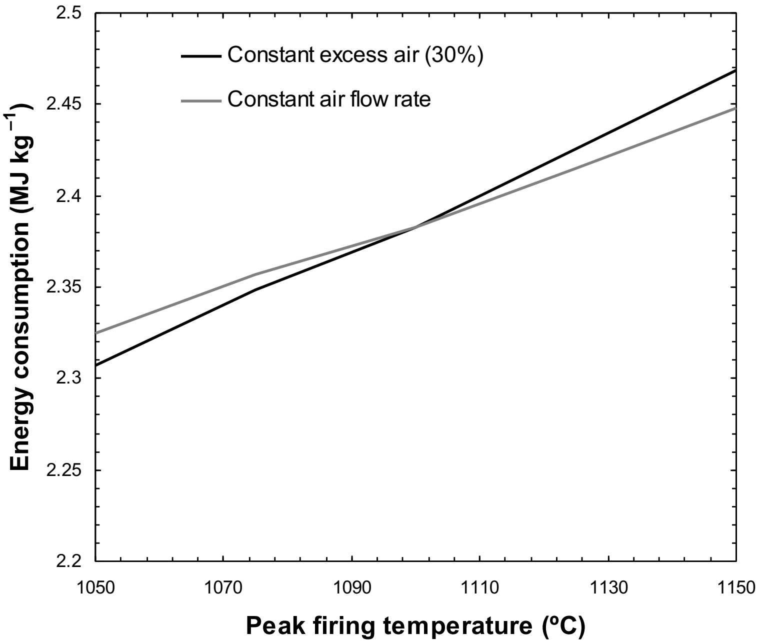

Figure 5. *Variation of energy consumption with peak firing temperature.*

Finally, Figure 6 shows the calculated effect of the modification of firing cycle length on energy consumption. When cycle duration decreased with relation to the reference duration of 50 min, specific consumption decreased, whereas when cycle duration increased, specific consumption rose. The effect observed was much more pronounced in the case of constant air flow rate.

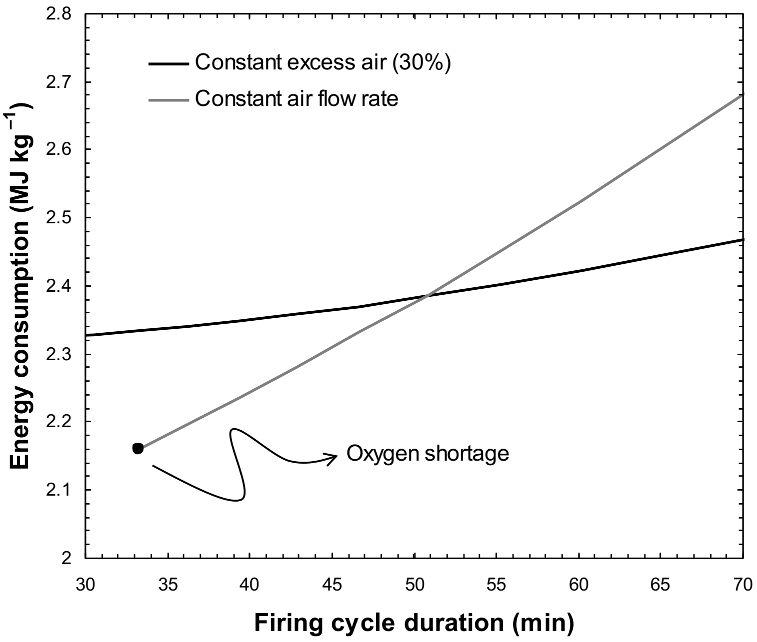

Figure 6. *Variation of energy consumption with firing cycle duration.*

Unlike what occurred in the previous cases, varying cycle duration modified the mass flow rate of the tiles fed into the kiln. In the previous cases, when the specific consumptions decreased, the same thing happened with absolute energy consumption in the kiln (energy consumed per unit time). When cycle duration decreased, however, absolute energy consumption in the kiln rose because the tile mass flow rate increased as consequently did the quantity of energy to be dissipated in the cooling, the heat of reaction to be contributed, etc. However, the increase in production partly offset this effect, so that specific energy consumption was lower.

As a result of the above, in this case, keeping a constant oxidising air volume flow rate accentuated the effects of the variations in cycle duration. This was because if, for example, cycle duration were shortened, kiln overall energy consumption would increase. As a result, if the initial air volume flow rate were held, the excess air would be reduced, with the ensuing reduction in specific energy consumption. This was so patent that, in the calculations, a situation was reached with an air shortage, shown in Figure 6.

7. CONCLUSIONS

This study describes the use of a theoretical energy transfer model in ceramic tile kilns for predicting the effect of certain aspects relating to the ceramic composition on energy consumption:

- The replacement of carbonates in earthenware wall tile compositions with other raw materials that do not undergo such noticeable endothermic transformations could lead to a significant reduction in energy consumption in firing.
- As might be expected, a reduction in peak firing temperature led to lower energy consumption. However, for that decrease in consumption to be substantial, the reduction in peak temperature would need to be significant.
- Shortening the duration of the firing cycle also led to a reduction in specific energy consumption, particularly when the action was performed without correcting the modification in excess air.

The developed theoretical model is not limited to predicting the influence of the ceramic composition, but it allows the impact of other kiln characteristics and/or operating conditions on kiln energy consumption to be studied.

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