

## Analysis of the MK brick kiln thermal behavior

### Análisis del comportamiento térmico de un horno ladrillero tipo MK

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#### Abstract

Historically, the artisanal brick firing process has been of low profitability and highly polluting, which are reasons why the MK kiln was designed as a mitigation alternative. This type of kiln has been poorly investigated from a scientific point of view; the present work presents further knowledge about the thermal behavior of the MK kiln during a typical brick burning process. Experiments were carried out under the conditions normally handled by the producer. The results exhibit the level of thermal homogeneity inside the kiln, as well as the influence of the combustion gas flow toward the chimney. An energy balance carried out shows the amount of energy required to raise the temperature of the bricks, as well as the heat losses through the walls, dome, supporting arches, and combustion gases, finding an energy efficiency of 44.09%. Furthermore, the compression resistance of strategically placed specimens was evaluated to observe the influence of the temperature on the quality of the product, observing that only 28.5% of the evaluated specimens exceed the applicable standard. Finally, design considerations for an MK kiln series that optimizes the burning process energy in a semi-continuous batch process are presented. This configuration could be a convenient alternative to brick producers associated as a cooperative.

**Keywords:** Kiln, brick, thermal behavior, firing process.

#### Resumen

Históricamente, el proceso de cocción de ladrillo artesanal ha sido de baja rentabilidad y altamente contaminante, por lo que el horno MK fue diseñado como una alternativa de mitigación. Este tipo de horno ha sido poco investigado desde un punto de vista científico; el presente trabajo presenta nuevo conocimiento sobre el comportamiento térmico del horno MK durante un proceso típico de quema de ladrillos. Los experimentos se llevaron a cabo en las condiciones que normalmente maneja el productor. Los resultados muestran el nivel de homogeneidad térmica dentro del horno, así como la influencia del flujo de gases de combustión hacia la chimenea. Se realizó un balance energético que muestra la cantidad de energía requerida para elevar la temperatura de los ladrillos, así como las pérdidas de calor a través de los muros, cúpula, arcos de soporte y gases de combustión, encontrando una eficiencia energética del 44,09%. Además, se evaluó la resistencia a la compresión de probetas colocadas estratégicamente para observar la influencia de la temperatura en la calidad del producto, observándose que solo el 28.5% de las probetas evaluadas superan el estándar aplicable. Finalmente, se presentan las consideraciones de diseño para una serie de hornos MK que optimiza la energía del proceso de combustión en un proceso semicontinuo. Esta configuración podría ser una alternativa más eficiente para los productores de ladrillos asociados como cooperativa.

**Palabras clave:** Horno, ladrillo, comportamiento térmico, proceso de cocción.

## 1 Introduction

Artisanal brick production is a major economic activity linked to home building, mainly in developing

countries, where the construction sector is considered to be a key factor in their economies (Cárdenas *et al.*, 2012). In Latin American nations, it is estimated that 30-50% of brick production comes from artisanal procedures (Cárdenas *et al.*, 2012).

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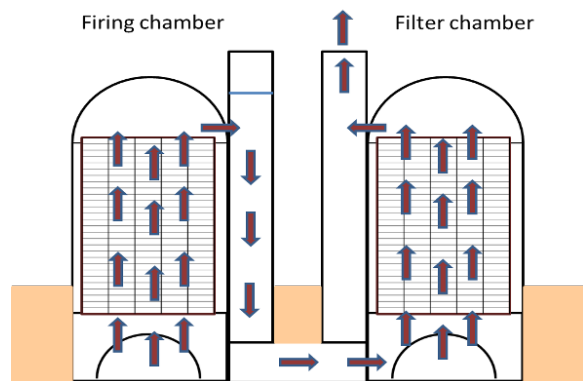


Fig. 1. MK2 kiln operation scheme for phase one burning. Source: Authors.

This fact has inherently generated excessive pollutant emissions due to the low heat transfer efficiency associated to artisanal methodologies. Reducing contamination requires process improvements in production practices, provided that the building industry of underdeveloped countries mainly uses artisanal burned bricks. One of multiple efforts made around the world to reduce contamination during the brick production process was the kiln proposed by Robert O. Márquez (Márquez, 2002; Corral-Avitia *et al.*, 2005; Zavala *et al.*, 2018), hence the acronym MK (Marquez Kiln). The MK2 kiln is still in its experimental stage (Cárdenas *et al.*, 2012) because it does not have a defined operation methodology, and hence the pieces produced are considered artisanal bricks. Márquez (2002) designed the MK2 kiln thinking of it as an ecological model, namely its design with two chambers, one functioning as a filter of the combustion gases generated in the brick firing chamber (Romo-Aguilar *et al.*, 2004). Both chambers, or kilns, are interconnected through their respective chimneys by two tunnels located at the level of the fireplaces, going from one another. This design takes the combustion gases from the firing chamber toward its chimney, then downward to the tunnel, and conducted to the other chamber which acts as a filter, and the gases are then exhausted by the chimney of the filter chamber (Fig. 1). The chimneys allow contamination assessment if appropriate measurement devices are available. This geometric configuration defines the brick firing cycle in two phases. The burning process starts with the two chambers loaded with raw bricks. Phase one begins when chamber one is fired, the hot combustion gases being conducted by its chimney downward through the tunnel toward the firing base of the other chamber, namely chamber two, where raw bricks serve as a filter

as the combustion gases ascend toward the chimney, Fig. (1). At the same time, heat stored in combustion gases is used to dry or preheat the raw bricks of chamber two. The combustion gases are thus guided with the help of appropriate valves at the upper section of the chimneys. In the second phase, chamber two (that worked as the filter in phase one) converts into the firing chamber (with dry and pre-burned bricks). Before chamber two is fired, chamber one should be unloaded of the fired bricks and reloaded with raw bricks (to work as the filter chamber for phase two of the burning cycle). Then, chamber two can be fired, whose hot combustion gases dry and pre-burn the raw bricks of chamber one, which acts as the filter chamber. The next cycle implies unloading and reloading chamber two to fire chamber one, and the burning cycle may continue.

In Mexico, the MK2 kiln competes with two other kiln designs. They are the traditional brick firing kiln and the fixed-wall kiln.

Traditional brick firing kilns are composed of three sections whose internal raw brick spacial location is built from bottom to top. The lower section usually has a fixed wall about one meter tall. The middle one, approximately two meters tall, is covered with two layers of movable burned bricks sealed with mud. The third and upper section of the kiln is only protected by a layer of burned bricks without mud. The ceiling of the kiln is free but covered, almost at the end of the firing process, with manure. Due to the characteristics of the wall sections, heat losses are high with burning gases escaping everywhere between the brick cover gaps in the upper third section of the wall and also through the brick ceiling gaps; as a consequence, this design does not really allow to assess contamination.

Fixed-wall kilns, on the other hand, are similar to the MK2 kilns in the sense that they also have wide fixed walls covering all the raw bricks, with the advantage of having a rectangular geometry that facilitates the brick spatial location. Contrary to MK2 kilns, fixed-wall kilns do not have chimneys where the contamination can be confined but a free ceiling, and thus gases are not easy to be quantified. The MK2 kiln design has the advantage of having chimneys concentrating the emitted gases, although the circular geometry makes difficult the rectangular brick internal location within. The chimney of the chamber that acts as a filter facilitates the assessing of contamination by measurements in a confined space. No matter what kind of kiln or brick formula producers use, they always struggle to have well-burned bricks, as well as reducing fuel consumption,

firing time, and contamination. These are key process issues that influence the profitability and productivity of any kiln and hence the business. In terms of quality, the compression resistance of the bricks is a strong factor to be accounted for in commercialization since they must comply with well-defined construction specifications (ONNCCE, 2012), in addition to the characteristic red color and sound of a well-burned artisanal brick. The most important step in the overall brick firing process is the firing one. Various combustible materials can be used to provide the necessary heat to arrive at the clay sintering chemical reactions. For this to occur, it is necessary to raise brick temperature to at least 800 °C (Martínez-González *et al.*, 2002), where the brick vitrification takes place. Vitrification is the term used to describe the sintering process of the clay, that is, the reaction between the individual solid particles of a substance to give a hard, less porous and somewhat smaller product (contraction). It usually takes place at a temperature lower than the melting point of the material (in the range 900-1200 °C), which should never be reached (Corzo *et al.*, 2013). Burning bricks up to 800 °C requires long times and high combustion loads. Contamination is therefore an issue that must be attended. Corral-Avitia *et al.* (2010) addressed the kiln location thinking of decreasing the pollution impact. They determined the effect of the kiln operation on the surrounding neighborhoods using a nine-digit estimated risk scale including a multi-criteria hierarchical analysis and the modified Delphi technique. In a further study, Corral-Avitia *et al.* (2010) determined the level of vulnerability of urban areas for the operation of the brick industry. A further study presented a comparison between the air pollution produced by a traditional brick kiln used in the north of Mexico (Ciudad Juarez, Mexico) and that of an MK2 kiln (Bruce *et al.*, 2012). Their basic idea was to assess the potential absorption of contaminating material in the filter chamber. The investigation also considered the performance of several rectangular open roof kilns, two prototype MK kilns (without connection between chambers), and two series of MK2-type kilns built in Ciudad Juarez. Bruce *et al.* (2012) concluded that the MK2 kilns have the potential to be a good choice toward the reduction of pollutant emissions.

Moreover, Violante-Cruz and Gallegos-Muñoz (2011) focused on improving the firing process of artisanal bricks by looking for, for example, the most appropriate materials that the kiln walls must have to improve energy efficiency by assessing a heat transfer

balance and some process diagnostics; they arrived at composite walls constituted in its outer layers by common bricks, a pocket of air in the middle, and a special insulating material with a suitable thickness. The issue is that artisanal brick makers, at least in Mexico, cannot afford special insulating materials. Torres-Ochoa *et al.* (2019) reported the development of a geopolymer using clays (a mixture of Kaolin, Tepozán and Bauwer) which adheres to the red brick; by using a response surface methodology technique, they showed that the geopolymer can be used as an internal coating in brick kilns to avoid premature cracking and thus extend their useful life (Torres-Ochoa *et al.*, 2019). Hinojosa-Ledesma and Velasco-Hurtado (2005) carried out a procedure to determine the thermal efficiency of a fixed-wall kiln by means of a heat energy balance. In a further publication, they showed the final results of the thermal balance for a 15,000-piece kiln, accounting for the areas of opportunity for heat losses of the kiln. They stated that it is difficult to maintain a close temperature range within the kiln (800-900 °C), pointing out a 22.0% energy efficiency (Hinojosa-Ledesma and Velasco-Hurtado, 2005). The rest of the energy is lost through the kiln walls and combustion gases (Hinojosa-Ledesma and Velasco-Hurtado, 2004). Speaking on energy as well, Munguía-Guillen *et al.* (2012) focused on the temperature profiles inside the MK2 kiln. They attribute the lack of thermal homogeneity to the fuel feeding technique of the producer.

The brick formulation may play an important role in brick quality, energy savings, and contamination reduction. Gökhan and Simsek (2013) studied the effects of rice husk on brick properties. They noted a decrease in apparent porosity, which invariably leads to a decrease in compressive strength, limiting the concentration of husk to 15% (Gökhan and Simsek, 2013). Similar results have been obtained with a mixture of sugarcane bagasse ash (SBA) and rice husk ash (RHA) (Kazmi, Munir, Patnaikuni *et al.*, 2018), although the inclusion of residual marble increases the concentration of the residue to 25% while obtaining similar mechanical characteristics as before (Munir *et al.*, 2018). In Mexico, for example, sugarcane bagasse is one of the most abundant and available agricultural residues that could be investigated further (González-Leos *et al.*, 2019).

Regarding inorganic residues, further improvements were achieved by using 25% of residual glass (Kazmi, Munir, Wu *et al.*, 2018), apparently due to the similarity between clay and glass at the sinterization point. Simoes dos Reis *et al.* (2020) used

residues from the construction industry; as before, both the firing temperature and the percentage of the residue influence the compressive strength, obtaining the best results at a temperature of 800 °C at 70% concentration. The authors point out that the use of such waste could have practical applications in terms of recycling aspects providing energy savings and helping to drive sustainability, development and circular economy during the manufacturing process of construction materials (Simoes dos Reis *et al.*, 2020).

Although the MK2 kiln is currently of limited use, further knowledge of its thermal behavior may lead to improvements in artisanal brick firing. No authors have dealt with the MK2 behavior as it is done here, as we deal with thermal behavior and energy efficiency regarding the quality of the bricks. The results may help to obtain a better temperature distribution, lower fuel consumption, improved brick quality, and lower contamination.

## 2 Materials and methods

### 2.1 Experimental work

An artisanal brick firing experimental process in an MK2 kiln was run under conditions that are normally handled by the brick producer. The research was carried out in a kiln located in a community of small brick manufacturers called “El Refugio”, which is in the limits of the urban area of the León, Guanajuato, Mexico. Previous to the brick firing process, some activities were carried out:

- 1.- MK2 kiln sizing. Although not reported here in detail, the kiln should be dimensionally characterized: internal and external diameters, fixed supporting arches, location of the chimney, curvature of the dome, fuel supply door size, thermocouple location, etc. Some of this information was obtained to be used in a further study of numerical simulation of the heat transfer process in the MK2 kiln that will be presented in a future publication.
- 2.- Brick arrangement. The spatial brick location for each level (bed) was registered, facilitating the calculation of the total count of pieces fired per bed.
- 3.- Fourteen thermocouples were arranged from outside in, in such a way that each tip was flush

with the inner wall of the kiln. The location and the nomenclature of the thermocouples is shown in Fig. (2). The following activities occurred simultaneously during the brick firing process:

- 4.- The fuel feedstock – pine wood pallet scrap and pine wood powder – was conveniently weighed before being fed to the kiln. The brick manufacturer, based on experience, fed the fuel in batches, from time to time, trying to have a uniform temperature throughout the fire base and firing chamber. During the raw brick arrangement, some charcoal was added over four beds – numbers 10, 15, 17 and 19 – to increase heat provision to the brick firing process in the upper section of the kiln.
- 5.- Fourteen temperatures were recorded by using a data logger (the instrument was developed internally and calibrated by the certified metrology department of CIATEC). These measurements were taken every two minutes, from the very beginning of the firing process up to 36 hours long. Type K thermocouples were used and purchased from AR Pirometria in Mexico.
- 6.- Fourteen temperatures were hand-recorded on the outer wall of the kiln just below each thermocouple; the time spacing was 20 min (an EXTECH 42540 infrared thermometer was used).

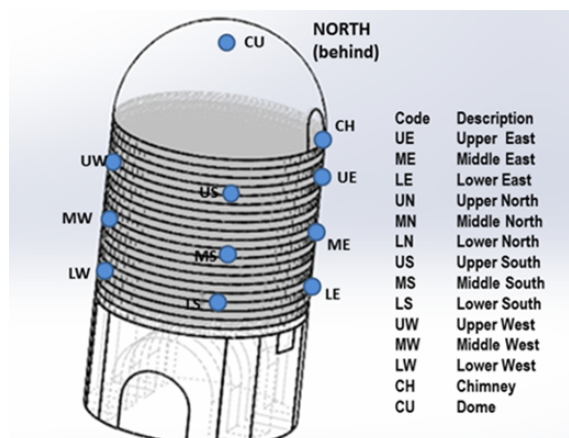


Fig. 2. Thermocouples locations. Source: Authors

## 2.2 Energy balance calculations

The energy supplied to the kiln is provided by the energy stored in the fuel fed to the kiln. The main objective is to use that heat to fire the raw bricks until they become burned bricks. However, there are some heat losses inherent in the process: heat loss through the kiln walls, heat absorbed by the brick supporting arches that form the ceiling of the firing chamber, and heat lost in the combustion gases. The energy balance also considers the ash remaining in the fireplace and the energy lost in the combustion gases.

### 2.2.1 Total energy supplied

The total heat supplied to the kiln was calculated on the basis of the combustion heat of each individual fuel supplied (pine pallet wood and pine wood powder) according to the Eq. (1), and the respective value found in the literature (Kollmann, 1959).

$$Q_T = \Delta cw1 \times mw1 + \Delta Hcw2 \times mw2 + \Delta Hcc \quad (1)$$

where  $Q_T$  is the overall energy that enters the kiln during the firing process (kcal);  $\Delta cw1$  is the combustion enthalpy for the pine wood pallet;  $mw1$  is the mass of the pine pallet wood;  $\Delta Hcw2$  is the combustion enthalpy for the pine wood sawdust;  $mw2$  is the mass of the pine powder wood; and  $\Delta Hcc$  is the combustion enthalpy for the charcoal.

The calculation of the energy supplied considered the following heat of combustion values (Kollmann, 1959): pine wood, 4,438.0 kcal/kg; pine sawdust, 4,500.0 kcal/kg; and charcoal, 7,897.0 kcal/kg.

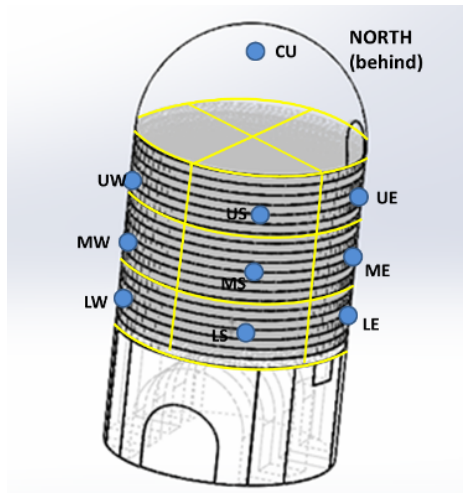


Fig. 3. MK2 kiln divided into sections to calculate the energy absorbed by the bricks. Source: Authors.

### 2.2.2 Energy absorbed by the bricks

To estimate the heat absorbed by the bricks, the kiln was divided in 12 sections, corresponding to the locations the 12 thermocouples around the kiln (Fig. 3). Each set of bricks was considered as a volume being at the temperature of the nearest thermocouple; it is assumed that all the bricks in the volume reached the maximum temperature detected by the thermocouple, although it is known that internal temperature profiles occur (Rodríguez-Ramírez et al., 2004). Eq. (2) was used to consider the sensible heat of the bricks.

$$Q_1 = mC_p(T_{max} - T_{initial}) = \Delta H_1 \quad (2)$$

where  $Q_1$  is the energy absorbed by the bricks (kcal);  $\Delta H_1$  is the enthalpy change;  $m$  is the mass of the raw bricks (kg) for each volume;  $C_p$  is the heat capacity (kcal/kg·K);  $T_{max}$  is the maximum temperature reached in each volume (°C); and  $T_{initial}$  is the initial firing (ambient) temperature (°C) This equation was also used to calculate the energy required to eliminate the moisture contained in the bricks.

$$Q_2 = mC_p(T_{max} - T_{initial}) = \Delta H_2 \quad (3)$$

where  $Q_2$  is the energy required to evaporate the raw brick moisture (kcal);  $\Delta H_2$  is the enthalpy change;  $m$  is the mass of the water contained in the raw bricks (kg) for each volume;  $C_p$  is the heat capacity of the water (kcal/kg·K);  $T_{max}$  is the maximum temperature reached in each volume (°C); and  $T_{initial}$  is the initial firing (ambient) temperature (°C).

### 2.2.3 Energy lost by the kiln walls

In general, empirical correlations for convective heat flow (Incropera and DeWitt, 2006) are of the form:

$$\overline{Nu} = \frac{\bar{h}}{k} L = CRa_L^n \quad (4)$$

where the Rayleigh number is

$$Ra_L = \frac{g\beta(T_s - T_\infty)L^3}{\nu\alpha} \quad (5)$$

$T_s$  is the surface temperature, and  $T_\infty$  is the fluid temperature.

For a vertical plate it is recommended to use a correlation that can be applied on the whole range of  $Ra_L$  (Incropera and DeWitt, 2006). It has the form:

$$\overline{Nu}_L = \left\{ 0.825 + \frac{0.387Ra_L^{1/6}}{[1 + (0.0492/Pr)^{9/16}]^{8/27}} \right\}^2 \quad (6)$$

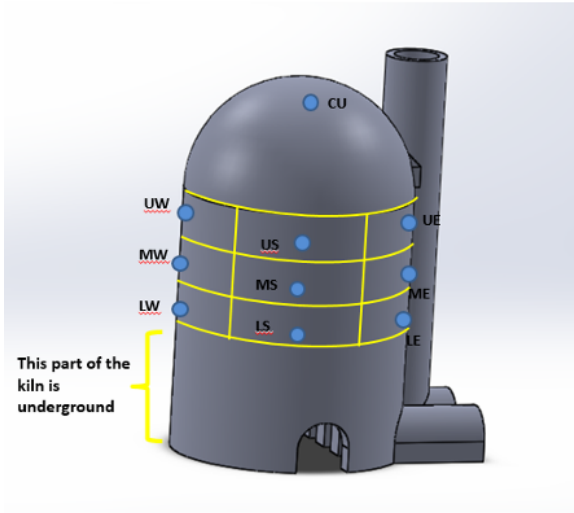


Fig. 4. MK2 kiln divided in sections to calculate the energy absorbed by the kiln walls. Source: Authors.

The Nusselt number was used to determine the convective heat transfer coefficients, both internal and external. These values were further used in Eq. (7) and (8) to assess the heat losses.

The wall curvature was neglected (flat surface), and the wall was considered as a homogeneous material made of bricks. Both internal and external convective coefficients ( $h_1$  and  $h_2$ ) were calculated altogether with the wall as a resistance series of Eqs. (7) and (8). For the calculations, the infrared temperatures at the outer face of the wall just next to the same positions of the thermocouples (Fig. 4) were used.

$$R_{tot} = \frac{1}{h_1 A} + \frac{L}{kA} + \frac{1}{h_2 A} \quad (7)$$

$$Q_3 = \frac{T_{\infty,1} - T_{\infty,2}}{R_{tot}} = \Delta H_3 \quad (8)$$

$Q_3$  is the energy absorbed by the walls (kcal) and dissipated to the ambient air. The calculations of Eq. (7) were carried out hourly to consider the nonlinearity with which the wall is being heated and the heat dissipation at the same time.  $T_{\infty,1}$  is the fluid temperature near the inner wall.  $T_{\infty,2}$  is the fluid temperature near the outer wall.  $\Delta H_3$  is the enthalpy change.

#### 2.2.4 Loss of energy through the kiln arches (supporting the bricks)

The MK2 kiln possesses fixed arches whose role is to support all raw brick beds above (Fig. 5).

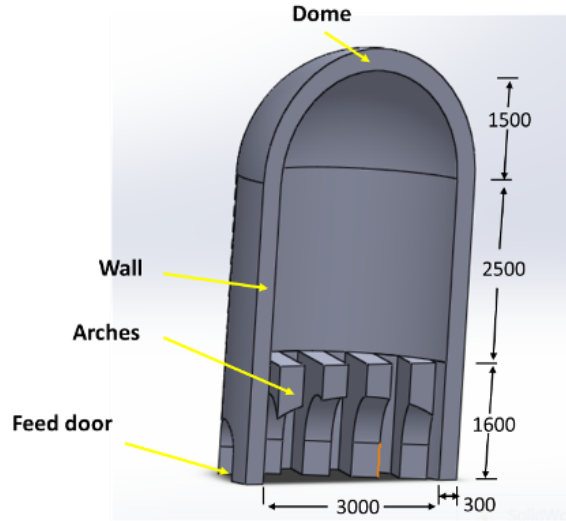


Fig. 5. Location of the support arches inside the MK2 kiln (lengths in mm). Source: Authors.

Underneath the fixed arches is the fireplace bed. The arch dimensions were used to determine its equivalent volume in raw bricks. Again, Eq. (2) is used to calculate the heat absorbed by the arches.

$$Q_4 = mC_p(T_{max} - T_{initial}) = \Delta H_4 \quad (9)$$

#### 2.2.5 Energy lost through combustion gases

The approximate calculation of the energy loss by the exhaust gases through the chimney considered the following assumptions:

- There is complete combustion of the fuel.
- The temperature read by the thermocouple placed at the exit of the chimney was used as the exit gas temperature.
- The combustion gas speed at the center of the exit chimney was measured with a Tenma 72-7595 device; the mass flow was calculated based on the Hagen-Poiseuille equation (Bird *et al.*, 1999) with respect to the maximum speed measured.

$$Q_5 = \sum (V_i C_p) T_{gases} = \Delta H_5 \quad (10)$$

where  $Q_5$  is the energy lost in the combustion gases (kcal);  $\Delta H_5$  is the enthalpy change;  $V_i$  is the volume of the exit gases; and  $C_p$  is the calorific capacity of the combustion gases (kcal/kg·K).

### 2.2.6 Ashes

The final residues were weighed and converted to heat in the same proportions of the fuel feedstocks. The calculated heat values were subtracted from the total equivalent fuel feed.

### 2.3 Resistance compression tests

The quality of the artisanal brick is commonly evaluated by the purchaser in a subjective manner; in practice, sample specimens are rarely sent to the lab for compression tests. Most customers are people who use them in small quantities; brick quality assessment is based on the shape, color, knock sound, and, in general, the appearance of the product. For research purposes, it was necessary to have an objective assessment of the brick compression resistance. Bricks were selected from different strategic areas of the kiln, including those pieces adjacent to each thermocouple tip. The idea was to have a reliable representation of the totality of the bricks in the kiln (Fig. 6).

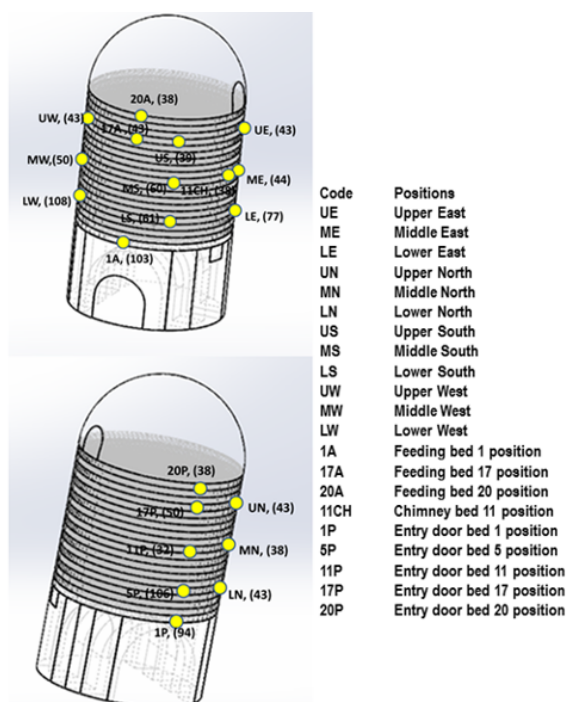


Fig. 6. Location of the brick specimens taken for compression tests (the number in the parenthesis represents the resistance of the brick in that position in  $\text{kg}/\text{cm}^2$ ). Source: Authors.

### 2.4 Marquez Kiln series efficiency

As designed by Márquez (2002), the system should have two chambers. However, under current operating conditions it is only possible to carry out half a cycle. During the first phase of brick firing, chamber one burns bricks while chamber two filters contamination and pre-burns and heats up raw bricks to around  $300\text{ }^\circ\text{C}$  (as measured in this research). However, it is not possible to take advantage of the pre-burning heat since burning in chamber two implies unloading and reloading chamber one. To unload chamber one, its bricks should be hand-manipulated cold bricks. Therefore, the second phase of cycle one starts burning chamber two with the raw bricks at ambient temperature in both chambers. Certainly some fuel will be saved because of the pre-burning of the bricks, but the pre-burning heat lost could also be used if a number of MK chambers could be added in series. We develop an MK-n design in order to define the optimal number of a series of MK chambers that decreases heat loss and increases productivity. The following considerations were taken into account (times have come from a series of burning cycles made in the MK2 kiln):

- Chamber loading time at daylight conditions: 12 h.
- Burning made the day after chamber loading, at daylight conditions.
- Burning time of raw bricks: 12 h.
- Burning time of pre-burned bricks, at daylight conditions: 9 h.
- Cooling time after burning: 50 h at  $50\text{ }^\circ\text{C}$ .
- Chamber unloading time at daylight conditions: 10 h.

## 3 Results and discussion

### 3.1 Thermal behavior

Figure (7) shows the thermal behavior all around the MK2 kiln inner wall. As expected, the higher temperatures are in the low section (low row of thermocouples, level L), the maximum values being around  $800\text{ }^\circ\text{C}$ . A certain parallelism between the curves of the four cardinal points monitored at this level (dot lines) can also be observed.

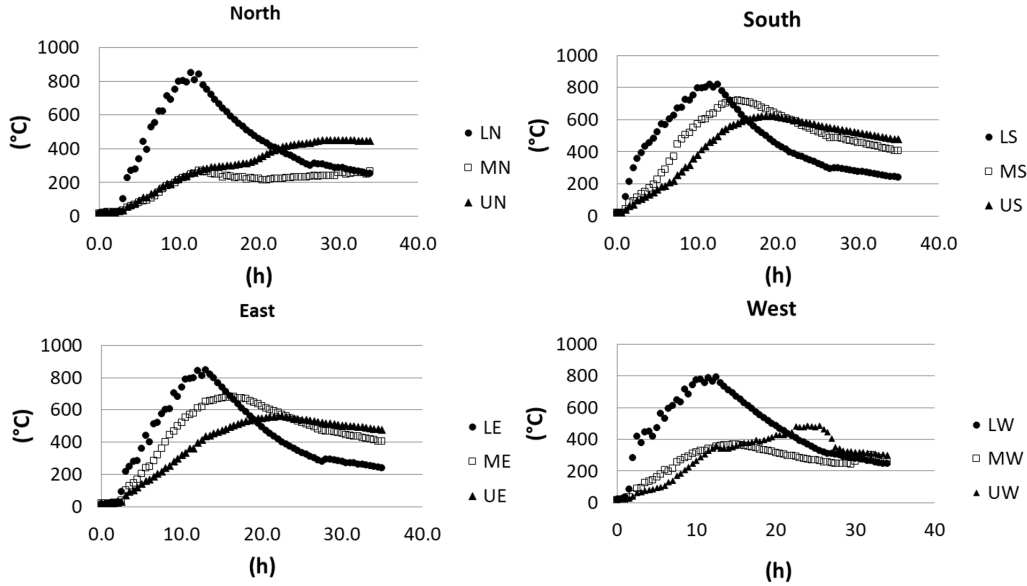


Fig. 7. Thermal behavior of the MK2 kiln internal wall surface. Source: Authors.

The scattering of the dots at the beginning of the firing is due to the intermittence with which the producer feeds the fireplace bed (Munguía-Guillen *et al.*, 2012). In the middle of the kiln (level M), South and East thermocouples are much hotter than those of North and West locations, although colder by about 150 °C than those of level L. East and South level M maximum temperatures are higher than the two other measurements carried out at the same level M (about 300 °C), as a result of the difficulty of the brick maker to maintain uniform temperatures throughout the kiln. This same thermal behavior repeats at level U, the upper section of the kiln, where South and East temperatures are again higher than the other two ones by about 150 °C. This is clear evidence of the non-uniformity of the temperature inside the MK2 kiln due to the positions of the feeding door (South) and the chimney (East). In fact, the maximum temperatures reached in the whole kiln are far from the expected set point of 800 °C according to the literature (Martínez-González *et al.*, 2002).

The chimney location is important. It surely affects on the non-uniformity in temperatures because the air entering the kiln may aerodynamically go from the fuel feeding door to the chimney; to arrange that phenomenon, some internal brick rearrangement should be made in order to compel the combustion air to go around and pass through the North and West regions of the chamber before arriving at the chimney. Further, the four cardinal references show, at some

time after 20 h, during the kiln cooling process, that temperatures are lower in the bottom section of the kiln and higher in the upper section. When the brick maker stops feeding the kiln, they close the feeding door, but they open it about 8 h later; the air entering by natural convection takes the stored heat from bottom to top. This phenomenon further heats the upper section, that is, heat is transferred from the bottom bricks to the upper bricks. The charcoal added at beds 10, 15, 17 and 19 serves also as an additional fuel that contributes to temperature in the upper section of the kiln.

Munguía-Guillen *et al.* (2012) reported that a high heterogeneity in the distribution of the temperatures in an MK2 kiln could be found, and stated that it occurred because of the fuel feeding technique. That is, it is done manually and by batches (intermittence), creating moments with high burning temperatures and moments with low burning ones (phenomenon that can be slightly seen in Fig. 7), as well as initial temperatures at level U, since the curves have been smoothed for clarity). This is certainly true, but it occurs mostly in the lower section of the kiln. Most importantly about the temperature homogeneity, regarding the quality of the bricks, is the original design of the kiln. Fig. (8) shows colorfully the maximum temperatures reached within the kiln, the pathway from the fuel feeding door to the chimney being the most “convenient” path for the combustion gases.



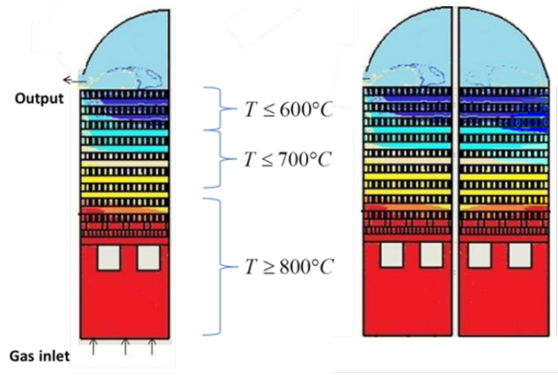


Fig. 8. Temperatures reached inside the MK2 kiln (experimental behavior). Source: Authors.

That is the main reason of the heterogeneity in the temperatures: the chimney location. The authors are dealing with the manner to improve the combustion gas distribution within the kiln so that a better temperature homogeneity can be found. Among them, brick relocation (closer in the chimney region) and redesign of the supporting arches are investigated. Further, a numerical design would be helpful since the brick arrangement could be selected as desired, and even a second chimney opposite to the current one could be numerically simulated.

### 3.2 Energy balance

The total energy supplied to the kiln is 4,425,129.8 kcal from 997.1 kg of pine wood, 2,400,750.0 kcal from 533.5 kg of sawdust, and 371,119.0 kcal from 47 kg of charcoal. By using the combustion heat of each fuel, the total amount of energy supplied is shown in Table 3.

This enthalpy is transferred from the fuel to the kiln in heating and burning the bricks, heat losses through the wall, heating of the support arches, and heat lost by the exiting combustion gases.

#### 3.2.1 Energy absorbed by the bricks

With regard to the energy consumed for warming up the bricks, a total of 5,105 bricks were processed.

Table 1. Maximum zone temperatures (°C). Source: Authors.

	South	East	North	West
Low	830	868	872	820
Medium	719	682	277	369
High	623	559	454	488
Dome	520	Door	450	

The  $C_p$  was considered constant for the raw and burned bricks with a value of 0.25 (kcal/kg·K) (Fontalvo Porras and Gutiérrez Robles, 2014). A constant and initial mass of 4.04 kg for raw bricks (average weight obtained from 30 specimens) was also assumed. Here, the 12 representative volumes of each nearest thermocouple (Fig. 3) were taken into account, whose maximum temperatures are shown in Table 1. According to the measurements made, the raw bricks contained an average of 2.5% moisture. These data were considered in the calculation of the energy necessary to evaporate the water contained within. The  $C_p$  of the water was considered constant and equal to 1.008 (kcal/kg·K) (Incropera and DeWitt, 2006).

#### 3.2.2 Energy lost by the walls of the kiln

The calculations of the heat losses through the walls also considered the kiln divided into 12 volumes, assuming that the internal walls reached a maximum temperature equal to that of the nearest thermocouple. The dome and loading door we considered with their respective width. The external temperature was determined by the infrared thermometer. We used the equations shown in Section 2.2.3 to obtain results shown in Table 2.

It is important to mention that the thickness of the loading door of the kiln is significantly thinner than the rest of the fixed wall of the kiln. The brick maker covers the door with bricks and seals the brick joints with mud. Thus, the loading door external temperature is much higher than the rest of the kiln, and therefore heat losses are much greater by unit area. As for the dome, there is also a much higher loss value, as a product of the greater area involved in the calculation.

Table 2. Heat loss estimation through the walls (kcal). Source: Authors.

	South	East	North	West
Low	10,046.66	9,766.93	10,004.07	10,081.83
Medium	19,563.19	18,740.38	6,135.95	9,048.03
High	14,970.81	15,260.29	9,086.06	9,586.49
Dome	119,795.11	Door	18,355.56	

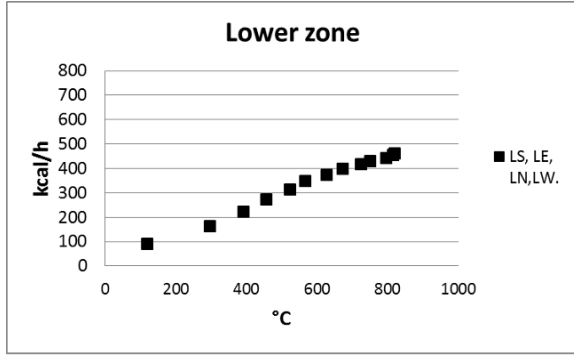


Fig. 9. Behavior of energy losses in the lower part of the kiln. Source: Authors

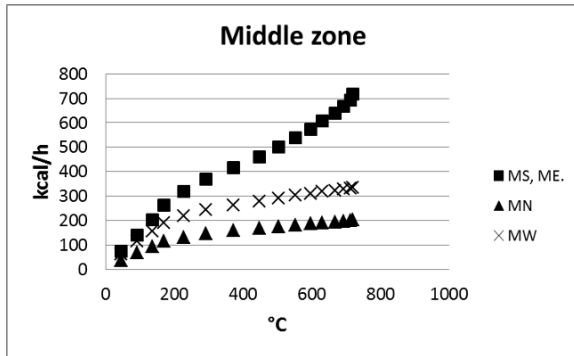


Fig. 10. Behavior of energy losses in the middle part of the kiln. Source: Authors

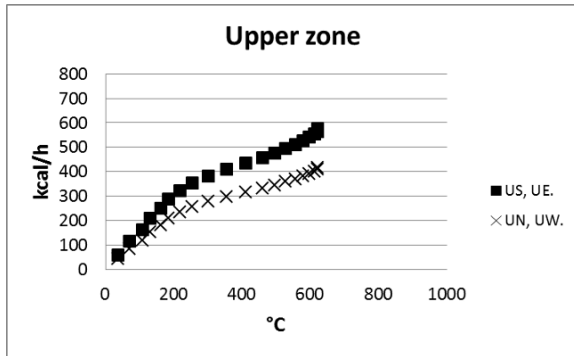


Fig. 11. Behavior of energy losses in the upper part of the kiln. Source: Authors.

The heat lost in the kiln is presented in Figs. (9) to (11). A symmetrical behavior is noticed in the lower level (the curves overlap, Fig. 9). In the middle level of the kiln, South and East sectors (MS and ME) are very similar in heat lost (Fig. 10). And in the upper section of the kiln, heat losses are similar in South and East (US and UE) and in North and West (UN and UW), Fig. (11). Every curve should be taken as

proportional between the average temperature at the corresponding section of the wall and the heat lost in that section. The higher the external temperature, the higher the heat loss.

### 3.2.3 Energy loss through the arches of the kiln (supporting the bricks)

The fixed arches of the kiln have a volume equivalent to 1,611 bricks; they are usually made of raw bricks that burn in the first fire. Therefore, in this experiment the  $C_p$  was considered constant for the arches (brick) with a value of 0.20 (kcal/kg·K) as burned bricks (Incropera and DeWitt, 2006).

A manner of increasing kiln productivity would be changing the fixed arches to movable brick arches (an idea that has not been found to be dealt with in other literature). As a first approximation, the additional burned bricks are 1,611 pieces. However, the movable brick arrangement cannot be done similarly to the current fixed-arch construction (it would be structurally unstable), but it may be similar to that made in traditional kilns (which are constructed from bottom floor to top). The real equivalent number requires getting rid of the fixed arches and substituting them with movable brick arches; the calculation arrives at about 1,000 pieces. The real increased productivity is around 20%, provided movable arches contribute at least with similar aerodynamics of the burning gases inside the kiln, that is, assuming that the overall heat transfer efficiency of the MK kiln is equivalently maintained.

### 3.2.4 Energy loss through the combustion gases

The energy lost by the combustion gases, Eq. (8), considers the temperature profile obtained by the thermocouple located at the chimney tower. The exit speed of the combustion gases measured with the anemometer, in the center of the chimney, had an average of 3 km/h. The  $C_p$  was considered in a range of values from 1.007 to 1.175 according to the temperature (kcal/kg·K) (Incropera and DeWitt, 2006).

### 3.2.5 Combustion residual material

The weight of residual material (ash) registered was 90 kg. The calculations are in the proportion 50.3:49.7 of wood to sawdust burned, as the fuel burned.

Table 3. Summary of the energy consumption Source: Authors.

	(kcal)	(kcal)	(%)
Total energy generated by combustion	-7,197,038.80		100
Energy consumed in the bricks firing ( $Q_1$ )		3,173,568.39	44.09
Energy consumed to eliminate the moisture within raw bricks ( $Q_2$ )		42,607.56	0.6
Energy lost by the walls ( $Q_3$ )		280,441.43	3.89
Energy absorbed by the arches ( $Q_4$ )		1,333,908.00	18.53
Energy lost in the exhausting gas ( $Q_5$ )		1,715,125.63	23.83
Energy loss associated with the assumptions of the model of heat transfer		250,014.79	3.4
Total energy loss		6,795,665.80	94.5
Ashes ( $Q_6$ )		401,373.00	5.5
Heat transfer balance	-7,197,038.80	7,197,038.80	0

Table 4. Energy comparison of the MK kiln and the kiln (HL) analyzed by Hinojosa-Ledesma and Velasco-Hurtado (2004). Source: Authors.

	MK		HL	
	(kcal)	(%)	(kcal)	(%)
Total energy generated by combustion	7,197,038.80	100	14,048,170.00	100
Energy consumed in the bricks firing	3,173,568.39	44.09	3,224,033.00	22.95
Lost energy	4,023,470.41	55.91	10,824,137.00	77.05

### 3.2.6 Total heat balance

The summary of the energy balance calculation is shown in Table 3. It can be noted that the brick firing takes about half of the total energy supplied to the system. The greatest heat loss is in the combustion gases; therefore, it is the main area of opportunity to increase the heat transfer kiln efficiency, that is, to increase the interfacial contact between bricks and hot gases. The energy lost by the walls of the kiln is relatively small, which is an effect of the 33-cm-thick wall, with an external temperature profile that increases from bottom to top. A thicker wall at the bottom of the kiln would help to even achieve a completely adiabatic wall in the entire volume of the kiln. Because of its large area, the dome loses an important amount of heat. The overall efficiency of the kiln is estimated at 44.09%; that is to say, less than half of the heat capacity stored in the fuel goes to the brick firing.

The estimated 3.4% wall heat loss is due to the assumptions of the calculations, such as constant properties of the materials, approximations of temperature of each one of the 12 volumes considered, the empirical correlations of the model for calculation of heat loss through the walls, average speed of exit of the combustion gases, variation in the initial mass of each raw brick, etc.

Table 4 globally compares the MK kiln with the kiln reported by Hinojosa-Ledesma and Velasco-Hurtado (2004) in terms of the energy consumed in the brick firing. No objective comparison can be made because no brick weight information is provided in the reference; what is clear is that the MK2 kiln experimented here, for 5,500 pieces, doubles the efficiency reported by Hinojosa-Ledesma and Velasco-Hurtado (2004), in a 14,000-15,000-piece kiln. It means that the MK2 kiln could be a good alternative in saving energy for burning bricks when compared to that reported by Hinojosa-Ledesma and Velasco-Hurtado (2004).

Table 5. Comparison with results reported by Munguía-Guillen *et al.* (2012).

	Brick tons. per firing	Energy fed (kcal/brick ton)	Burned bricks (%)
Kiln 2 (San Miguel de Allende), firing 1.	16.2	358,509.00	60.0
Kiln 1 (San Miguel de Allende), firing 2.	16.2	860,421.60	50.0
Kiln 2 (San Miguel de Allende), firing 3.	20.5	358,509.00	50.0
Kiln 2 (San Miguel de Allende), firing 4.	9.9	1,003,825.20	50.0
Kiln 3 (Aguascalientes), firing 5.	39.0	1,386,234.80	90.0
Kiln (El Refugio, León, México)	21.13	340,531.86	31.5

Further, Table 5 compares results obtained here with those of Munguía-Guillen *et al.* (2012) for five brick firings in three different MK2 kilns. They reported better heat transfer efficiencies than that obtained here for similar burning procedures; from the information provided by Munguía-Guillen *et al.* (2012), it is not possible to assess the reason for the differences in the heat transfer efficiencies, such as brick spacing, brick formulation, fuel feeding technique, for example.

### 3.3 Resistance to compression tests

A series of burned bricks were selected, most of which were located right next to each thermocouple tip, in addition to some other strategic locations within the kiln, as shown in Fig. (6). The minimum compression resistance is 70 kg/cm<sup>2</sup> for loaded brick walls, according to the Mexican Standard NMX-C-404-ONNCCE. Fig. (12) shows that most of the brick specimens taken do not comply with the specification, that is, 71.5% of the total number of fired bricks. Rodríguez-Ramírez *et al.* (2004) and Márquez (2002) pointed out that the quality of the brick is related to the temperatures reached by the brick. The results obtained here seem to confirm that the bricks that attained temperatures greater than 800 °C complied with the standard. The resistance to compression tests should be, somehow, proportional to the temperature and time reached by each single brick (Márquez, 2002).

The MK kiln presents acceptable compression values in zones where the appropriate temperature is reached (800 °C). This quality is better than other studies reported, values lower than 40 kg/cm<sup>2</sup> (Piscal Arevalo *et al.*, 2012). Another study shows good results with the difference that its process was carried out in an industrial oven where it is relatively easier to maintain adequate temperatures around the bricks (between 900 and 1000 °C) (González García and Lizarraga Mendiola, 2015).

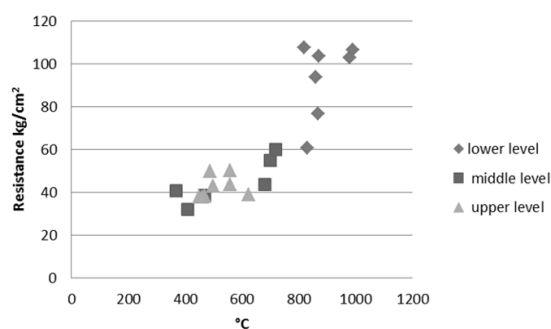


Fig. 12. Compression test values for the brick specimens. Source: Authors

An analysis of variance (ANOVA) was carried out, with a confidence level of 0.95, to statistically verify if the temperature reached by the bricks influences the compressive strength. A single factor was considered, which is the temperature corresponding to three intervals, from 801 to 1000 °C (level L), from 601 to 800 °C (level M), and from 401 to 600 °C (level U). It is known that the null hypothesis is that there is no significant difference in the means, in this case regarding the three temperature levels, which is discarded with the ANOVA shown below:

The null hypothesis is discarded since the value of  $f = 38.83$  is greater than  $f_{0.05, 2, 17}$ . The assumptions of the normal model, constant variance and independence are corroborated. It can be observed that the level of the factor that shows better results is level L, that is, it is also statistically recommended to reach temperatures higher than 800 °C.

On average, the raw brick mass was 4.14 kg, with a volume of 0.00244 m<sup>3</sup> and a density of 1696.1 kg/m<sup>3</sup>. Once the firing process was carried out, the brick presented an average mass of 3.84 kg, a volume of 0.00239 m<sup>3</sup> and a density of 1604.1 kg/m<sup>3</sup>, and there was a loss of 5.5% in density. Regarding the color, the brick produced was considered a good quality batch since there was an adequate red color homogeneity. Bad quality means a dark color at the end of the firing, similar to that of the original clay used.

Table 6. Compression results versus temperature in an ANOVA table. Source: Authors.

Source	GL	SC	CM	f	P
Temperature	2	11262	5631	38.83	0.000
Error	17	2465	145		
Total	19	13727			

R-squared	82.04%
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The MK2 kiln is apparently a very energy efficient kiln in terms of heat transfer efficiency. But, in this investigation, only 31.5% of the brick specimens tested reached 800 °C (6 pieces against 19), one of them not complying with the compression standard. None of the other specimens reached neither the standard nor 800 °C. Munguía-Guillen *et al.* (2012) reported a 50% brick burning efficiency, but quality was assessed subjectively on the basis of brick appearance (no compression test were reported). Hinojosa-Ledesma and Velasco-Hurtado (2004) assessed bricks in a similar manner, reporting a 22.95% heat transfer efficiency, but no clear information was stated about brick quality.

As a result, the MK2 kiln has opportunities for improvement, that is, temperatures throughout the kiln should reach at least 800 °C. As a virtual exercise, a calculation has been made to take all the MK2 bricks to at least 800 °C so that every single brick should comply the standard. The answer is that the burning process should continue to provide additional heat of about 1,205,720.9 kcal directly to bricks. Since the kiln has a 44.09% heating efficiency, the estimated total heat provided to the bricks should be 2,734,681.12 kcal. Summing up all

the energy that should be supplied to the kiln, it arrives at 9,931,719.92 kcal, providing heat losses are maintained in the same proportion of Table 3.

### 3.4 MK Series

A series of MK kilns were developed in order to assess the number of chambers that may be designed in an MK-n arrangement as a semi-batch process. This is done because of the intrinsic MK2 functioning, that is, heat is lost when the filter chamber cools before being actually fired. Arrangements from one to six chambers have been analyzed, the criteria being shown in Section 2.4.

Figure (13) shows that an MK-6 arrangement is the optimal burning, that is, under the conditions stated before, when chamber 7 is burned it actually corresponds to chamber 1, so that a new cycle starts. Therefore, should an MK system be built in a brick making field, it is suggested to arrange them in a hexagonal configuration, providing brick makers agree to burn from time to time as a cooperative union. This configuration is capable of burning up to 33,000 pieces every 6 days (per complete cycle), with enough competitiveness with respect to industrial brick making.

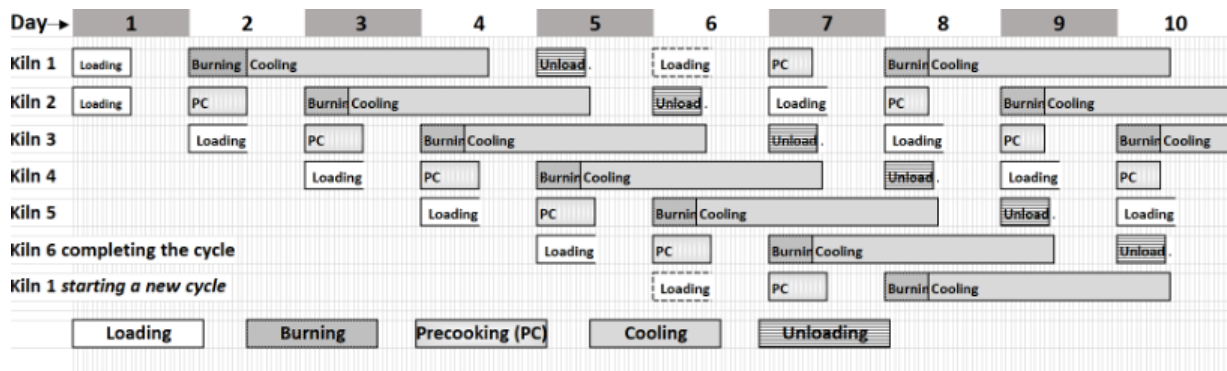


Fig. 13. Scheme of a MK-n burning process. Source: Authors.

## Conclusions

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- Only 44.09% of the total heat supplied was absorbed by the bricks, and 23.83% was lost in the combustion gases. Therefore, the MK kiln needs to be redesigned (brick location) so that heat transfer efficiency is increased to a better contact between combustion gases and raw bricks, as well as to raise internal temperature homogeneity.
- A further efficiency increase is to substitute the fixed supporting arches for in-situ built arches made of raw bricks. It may represent about 20% brick burning productivity of the kiln using a similar amount of heat. The new movable supporting arch design may help to increase temperature homogeneity.
- The energy loss by the walls is less than 4%. This value is sufficiently low as to consider the MK2 kiln adiabatic in future calculations.
- The MK kiln shows good potential to comply with Mexico's national specifications for compression tests provided that, from the statistics presented, minimum temperature of 800 °C is reached.
- The MK6 arrangement is the best configuration to be used. In this way, not only brick pre-burning but also heat savings and lower contamination can be advantages.
- These results provide further understanding of the thermal behavior of the MK kiln presented here. Improvements in heat transfer efficiency and temperature homogeneity inside the kiln are key issues in order to increase the overall brick compression resistance, hence brick quality, and to decrease contamination and fuel consumption. The changes should be performed in the field, feasible, and easy for the brick maker. Numerical tools may be useful in order to assess improvements in the MK kiln burning process for the betterment of the brick industry.

### Future research

Work will continue in searching for improvements and understanding of the MK2 kiln. One objective is

to develop a numerical simulation model capable of representing the heat transfer process in the kiln and to evaluate some different improvement options before implementing them on site. Numerical simulation has been used with good results to simulate models as varied as the corn nixtamalization process (García-Armenta *et al.*, 2020) or a thermal study of a solar distiller (García-Chávez *et al.*, 2020). The MK2 kiln numerical model will use as inputs the data obtained in this work, in addition to supporting the pertinent governing equations.

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