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Energy lost in endothermic reactions in the production of clay blocks in a continuous kiln

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Abstract. In Ocaña, Norte de Santander, Colombia, the production of ceramic materials is done in a traditional and empirical manner, generating heat losses, low productivity and product quality, and increased emissions of polluting gases into the environment. A virtual instrument for temperature data acquisition was developed and the firing process was monitored in two loading doors of a Hoffman kiln. 29040 blocks were produced, and 1370.76 kg of pulverized charcoal were consumed. The firing process lasted sixty-two hours and the virtual instrument was programmed to record data every 5 minutes. The energy supplied to the brick kiln was 340.16×10^6 kJ and the heat due to loading of the products and heat lost in the endothermic reactions of the clay was 107.71×10^6 kJ and 105.71×10^6 kJ respectively, representing 31.66% and 31.08% of the energy supplied. The results have made it possible to establish trends in the temperatures and energy consumed in the endothermic reactions in the clay. This will allow the implementation of coal quality and grinding procedures, increasing energy efficiency, and reducing gas emissions into the environment, thus avoiding acute respiratory diseases.

1. Introduction

The ceramics sector in Colombia, lacks technology in its production processes [1], leading to poor combustion processes that generate environmental and health problems due to polluting emissions [2], causing unnecessary costs for the companies [3]. An inadequate combustion process requires the use of larger amounts of fuel [4] and exposes companies to fines for failing to meet environmental standards [5].

In the municipality of Ocaña, Norte de Santander, Colombia, the production of ceramic materials is done in an empirical and artisanal [6] manner. Kilns are built with non-insulating materials that generate heat losses [7], have low production and thermal efficiency [8]. Also, they do not have controls in the extrusion and firing processes [9] and their products do not meet quality standards [10].

In the manufacturing process of ceramic products in the city Ocaña, Colombia, should strategies and control systems be implemented to reduce energy consumption and gas emissions into the environment, as well as to meet product quality standards.

The objective of the research is to monitor the temperatures of the combustion product gases with a virtual temperature data instrument [11], which allows the evaluation of the energy lost in the

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endothermic reactions of the clay in order to implement control systems that improve the combustion of the firing process.

2. Methodology

The study used a Hoffman continuous kiln of "ladrillera Ocaña", Colombia, [12], which produces H-10 horizontally perforated units, composed of two rows with 24 chambers or doors for product loading, and 5 stacks of 620 blocks are loaded in each door, which are separated by 60 cm between them.

2.1. Coal preparation and injection system

The fuel used is coal, which is stored in a storage yard and prepared by hammer mills into tiny particles, which are conveyed to the top of the kiln by a conveyor belt system. Fuel injection begins with a first coal dosifier that starts preheating the brick located in two chambers before the second coal dosifier passes through, re-burning the brick. Coal is injected at a rate of 8 kg to 12 kg of coal per minute and coal consumption is 170 tons/month [13].

2.2. Temperature data acquisition system and temperature profiles

The acquired temperature data was achieved due to the design, programming, validation, testing, configuration and visualization of a temperature data acquisition system, based on the DAQ assistant software executable of the compact RIO embedded system. In the data acquisition process, an NI 9213 I/O acquisition card was used, which is assembled to the NI cDAQ-9184 chassis, allowing the analog-digital processing of the information received from the installed thermocouples, to be stored through the Lab view software in the acquisition report to finally generate the temperature profiles in the kiln firing process. Type K bulb thermocouples with ceramic insulation were used to measure the temperature of the products and combustion gases.

2.3. Energy supplied by the fuel

This is the energy supplied due to the combustion of the coal used in the firing process, in the evaluation of this heat, the following expression is used, see Equation (1) [14].

$$Q_H = P_c * m_c, \tag{1}$$

where Q_H= heat input in (kJ), P_c= calorific value of coal in $\left(\frac{kJ}{kg}\right)$, and m_c = fuel mass in (kg)

2.4. Heat per load of the material to be fired

This is the heat required by the products to carry out the firing process, and the following expression is used to evaluate this heat, see Equation (2), Equation (3) and Equation (4) [14].

$$Q_{cm} = Q_{cm\ L1} + Q_{cm\ L2}, \tag{2}$$

$$Q_{cm\ L1} = m_{se\ L1} * C_{om} * (T_{máx} - T_{mín}), \tag{3}$$

$$Q_{cm\ L2} = m_{se\ L2} * C_{om} * (T_{máx} - T_{mín}), \tag{4}$$

where Q_{cm}= heat per load to be fired in (kJ), $Q_{cm\ L1}$= heat per load to be fired of H10x30x20 brick in (kJ), $Q_{cm\ L2}$ = heat per load to be fired of H10x40x20 brick in (kJ), $m_{se\ L1}$ = dry mass of H10x30x20 bricks in (kg), $m_{se\ L2}$ = dry mass of H10x40x20 bricks in (kg), C_{om}= specific heat of the brick material in $\left(\frac{kJ}{kg-K}\right)$, $T_{máx}$= material outlet temperature in (℃), and $T_{mín}$= material inlet temperature in (℃).

2.5. Heat to remove moisture from the material

This is the heat required to evaporate the water from the process, which has remained after drying, in the evaluation of this heat, the following expression is used, see Equation (5), Equation (6), and Equation (7) [14].

$$Q_{wm} = Q_{wm\,L1} + Q_{wm\,L2} \quad , \tag{5}$$

$$Q_{wm\,L1} = m_{t\,L1} * y_{m\,L1} * (h_g - u_m), \tag{6}$$

$$Q_{wm\,L2} = m_{t\,L2} * y_{m\,L2} * (h_g - u_m), \tag{7}$$

where Q_{wm} = heat to remove the moisture from the material to be fired in (kJ), $Q_{wm\,L1}$ = heat to remove moisture from H10x30x20 bricks in (kJ), $Q_{wm\,L2}$= heat to remove moisture from H10x40x20 bricks in (kJ), $m_{t\,L1}$= total mass of H10x30x20 bricks in (kg), $m_{t\,L2}$ = total mass of H10x40x20 bricks in (kg), $y_{m\,L1}$= moisture of H10x30x20 brick in (%), $y_{m\,L2}$= moisture content of H10x40x20 brick in (%), h_g= enthalpy of water vapor in $\left(\frac{kJ}{kg}\right)$, and u_m= internal energy of the water inside the material at a temperature of 20 ºC in $\left(\frac{kJ}{kg}\right)$. To evaluate the heat required to evaporate the water from the products, the enthalpy of the water vapor at a temperature of 150 ºC and the internal energy of the material to be fired at 20 ºC were taken [15].

2.6. Heat required for chemical decomposition of clay

This is the heat required for the chemical decomposition of the carbonates present in the clay, the following expression is used in the evaluation of this heat see Equation (8), and Equation (9), and Equation (10) [14].

$$Q_{dq} = Q_{dq\,L1} + Q_{dq\,L2}, \tag{8}$$

$$Q_{dq\,L1} = m_{se\,L1} * C_{dq}, \tag{9}$$

$$Q_{dq\,L2} = m_{se\,L2} * C_{dq}, \tag{10}$$

where Q_{dq}= heat required for the decomposition of the clay in (kJ), $Q_{dq\,L1}$= heat required for the clay decomposition of H10x30x20 bricks in (kJ), $Q_{dq\,L2}$= heat required for the clay decomposition of H10x40x20 bricks in(kJ), $m_{se\,L1}$ = dry mass of H10x30x20 bricks in (kg), $m_{se\,L2}$= dry mass of H10x40x20 bricks in(kg), and C_{dq} = specific heat from combustion of carbonates $\left(\frac{kJ}{kg}\right)$. To evaluate the heat required to break down the molecular structure of the clay and release the water from the combination of materials was evaluated at a temperature of 600 °C [15].

2.7. Heat to remove moisture from coal

This is the heat necessary to remove the moisture from the carbon, the following expression is used in the evaluation of this heat, see Equation (11) [14].

$$Q_{wc} = m_c * y_c * (h_{ga} - u_c), \tag{11}$$

where Q_{wc} = heat to remove moisture from coal in (kJ), m_C = mass of coal consumed in each period of time in (kg), y_C = coal moisture in (%), h_{ga} = enthalpy of water vapor at the temperature of the stack gases in $\left(\frac{kJ}{kg}\right)$, and u_C = internal energy of water in coal in $\left(\frac{kJ}{kg}\right)$.

2.8. Heat to remove water formed during combustion

This is the heat absorbed by the water formed by the combustion of hydrogen, which is heated, evaporated, and superheated to the temperature at which it exits with the fumes, the following expression is used in the evaluation of this heat, see Equation (12) [14]:

$$Q_{ac} = m_{cu} * m_{ac} * \left(h_g - u_m\right), \tag{12}$$

where Q_{ac}= heat to remove water formed in the combustion in (kJ), m_{cu}= mass of coal consumed in each period of time in (kg), m_{ac}= mass of water formed in the combustion in $\left(\frac{kg\ H_2O}{kg\ Comb}\right)$, h_g= enthalpy of water vapor throughout the process in $\left(\frac{kJ}{kg}\right)$. and u_m = internal energy of the water inside the material at a temperature of 20 ºC in $\left(\frac{kJ}{kg}\right)$; for the elemental composition of coal, emission factors are chosen for Colombian fuels, as listed by the "Unidad de Planeación Minero Energética", Colombia [16].

2.9. Heat to remove moisture in the air

This is the heat required to remove the natural moisture present in the air, which depends on the atmospheric conditions of the location, the following expression is used to evaluate this heat, see Equation (13) [14].

$$Q_{wa} = m_{wa} * m_{rm} * m_{cu} * \left(h_g - h_{wa}\right), \tag{13}$$

where Q_{wa}= heat to remove moisture in the air(kJ), m_{wa}= air humidity mass in $\left(\frac{kg\ H_2O}{kg\ Aire}\right)$, m_{rm}= dry air mass in $\left(\frac{kg\ Aire}{kg\ Comb.}\right)$, m_{cu}= mass of coal consumed in each period of time in (kg), h_g= enthalpy of water vapor in $\left(\frac{kJ}{Kg\ de\ agua}\right)$, and h_{wa}= enthalpy of water in $\left(\frac{kJ}{kg\ de\ agua}\right)$.

3. Results and discussions

27060 H 10x30x20 bricks with an average moisture content of 6.16% and 1980 H 10x40x20 bricks with an average moisture content of 2.95% were fired using 1370.76 kg of pulverized charcoal.

3.1. Virtual instrument validation

The data acquisition software was programmed to record temperatures every 5 minutes and the monitoring lasted sixty-two hours, the thermocouple recorded 744 data. The temperature profile generated from the combustion gases and theoretical clay firing curve can be seen in Figure 1.

The comparison of the theoretical temperature curve established by Munier, in Chaleur et Industries was carried out using a thermodilatometric analysis of the clay [17] with the actual firing curve of the clay obtained from the temperature acquisition. As the firing of the products is carried out due to heat transfer by radiation, the curve of the combustion gases is compared with the theoretical firing curve of the clay [17], in which there is a mismatch during the first hours of preheating in the products. On the other hand, the gases did not reach 400 °C during the first 6 hours of firing. As a result, the clay's water extraction period was extended, causing an increase in the propagation of water vapor, expansion of the clay pastes and release of a greater amount of smoke.

In the following 6 hours, the decomposition phase of the organic matter takes place and the clay curve used shows a high heating rate, reaching its maximum slope at 600 °C, causing the pieces to crack

on the faces and edges most directly exposed to the fire. The maximum temperature of the gases is 800 °C, making the maturation phase of the clay complete. Finally, the temperature of the gases begins to decrease, allowing the products to begin to cool, gradually lowering their temperature and withstanding the stresses produced by a rapid cooling process.

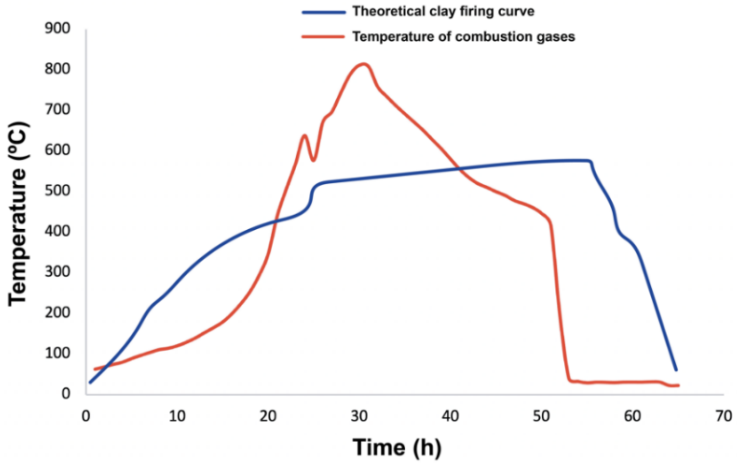


Figure 1. Temperature of combustion gases and theoretical clay firing curve.

3.2. Energy evaluation in the kiln

For the evaluation of the heat to remove water formed during combustion, the elemental composition of coal was used, taking into account the emission factors of Colombian fuels, related by the "Unidad de Planeación Minero Energética", Colombia [16]. The most important contraction of the clay in the firing process occurs between 800 °C and 900 °C [17], but although the gas reaches the maximum temperature of 800 °C, it does not remain uniform throughout the firing process. As a result, differences in contraction occur between the coldest and hottest areas of the products, causing cracks.

In the Figure 2, of the 105.71×10^6 kJ consumed by the endothermic reactions of the clay, 23.31×10^6 kJ were consumed to remove the moisture from the material to be fired which means 6.85% of the energy supplied. 58.67×10^6 kJ were used in the decomposition of the clay to remove moisture from the material to be fired corresponding to 17.24%. 1.03×10^6 kJ were used to remove moisture from the charcoal with 0.30%, 12.96×10^6 kJ to remove water formed in the combustion with 3.81%, and 9.43×10^6 kJ to remove moisture from the air with 2.77% of the energy supplied.

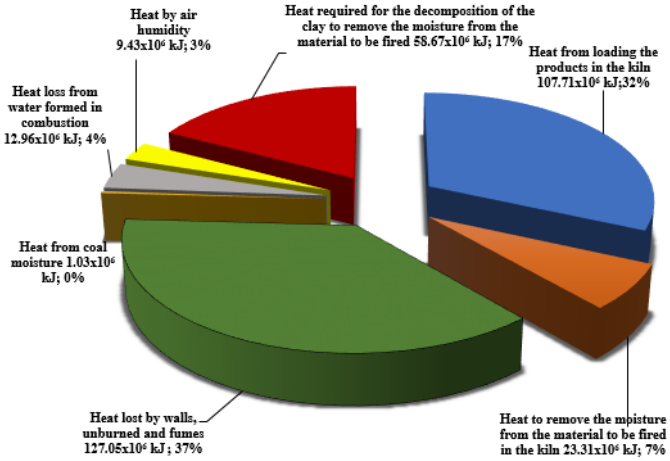


Figure 2. Energy balance in the kiln.

In comparison with an energy study in a beehive kiln [18], the energy consumed by the batch in the Hoffman kiln with respect to the beehive kiln was 107.71×10^6 kJ and 7.54×10^7 kJ and the energy consumed by the endothermic reactions of the clay was 105.71×10^6 kJ and 7.30×10^7 kJ corresponding to 31.08% and 12.71% of the energy supplied respectively.

4. Conclusions

The mismatch between the gas temperature curve and the theoretical firing curve of the clay can lead to a real acid rain on the dry material, hollowing out its entire structure and staining the surfaces exposed to the gases. The increase in the temperature of the combustion gases results in a high heating rate in the products, with a maximum slope at 600 °C, which occurs as the coal dosifier approaches the material. The recorded temperature increases above 20 °C per hour for the firing stage, affects the quality standards of the products.

The temperature of the gases must be gradually increased to carry out the firing process of the products. Likewise, the cooling rates must be moderate. Otherwise, there will be differences in contractions between the coldest and hottest areas of the stack, which would generate dangerous tensile stresses and cracks. The energy percentage of the endothermic reactions of the Hoffman kiln with respect to the beehive kiln was 31.08% and 12.71% respectively of the total energy supplied, which corresponds to a higher energy consumption of 32.71×10^6 kJ in the Hoffman kiln with respect to the beehive kiln.

Therefore, one measure to mitigate the indirect loss attributable to coal supply is to implement a quality procedure and minimum requirements for coal purchase and to implement coal grinding that leads to an adequate granulometry.

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