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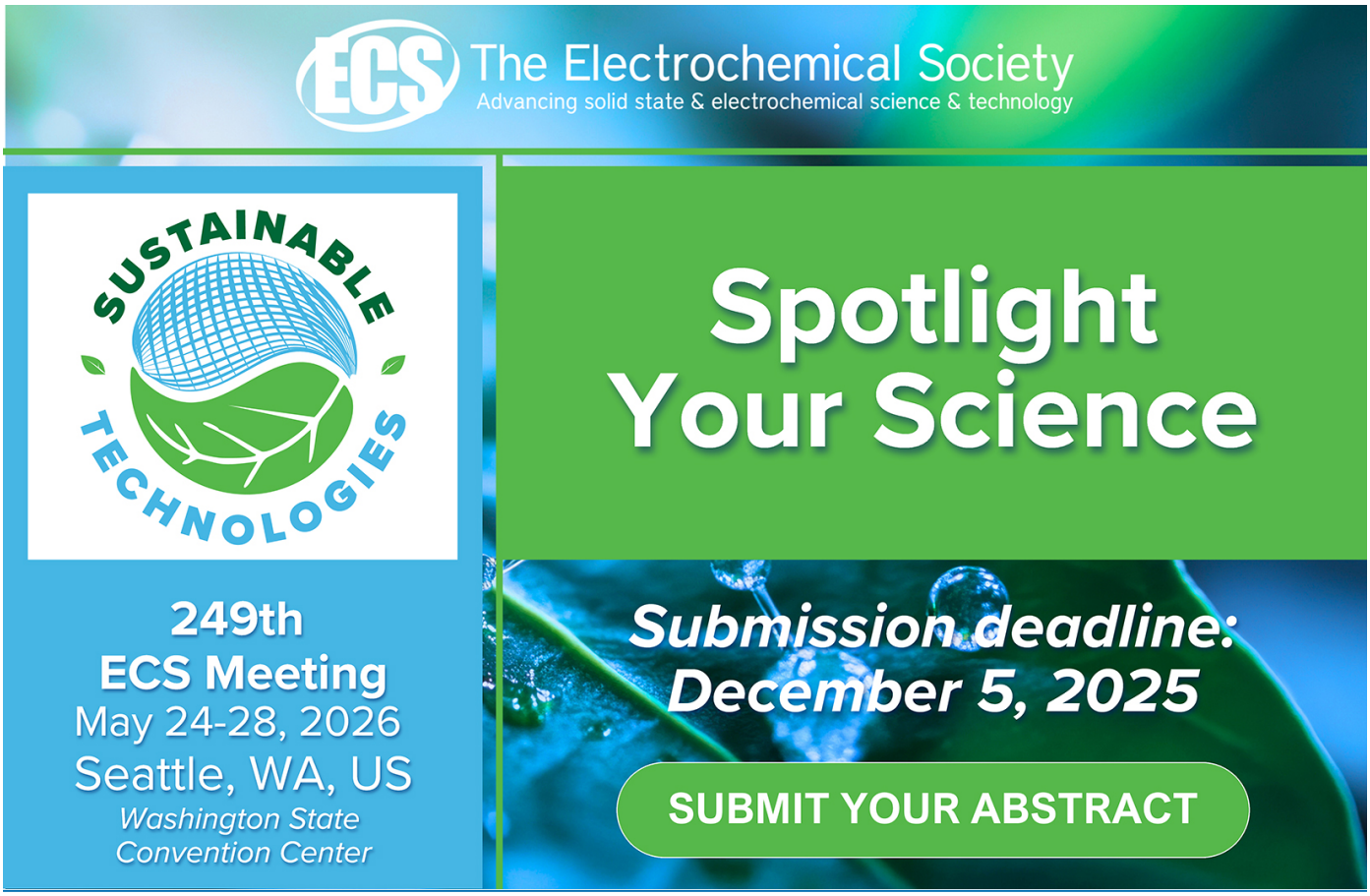
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Determination of connective heat transfer coefficients in an intermittent kiln

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Abstract. The determination of heat transfer coefficients are parameters of great importance when evaluating thermal losses in a system. Therefore, the present work reports the convective heat transfer coefficients in different positions of a rectangular kiln for the production of artisanal ceramic materials, located in Ocaña, Norte de Santander, Colombia, from which the heat losses present in the were determined. As a result, a virtual instrument was designed for temperature acquisition, using a data acquisition card, as well as a chassis and thermocouples generating a temperature report and their respective temperature profiles. The determination of heat transfer coefficients are parameters of great importance when evaluating thermal losses in a system. The energy supplied by the fuel is 51.21 kJ and the energy loss in the walls and floor of the brick kiln is 17.67 kJ, which represents 34.51% of the energy supplied. The thermal gradient in the kiln is not homogeneous, affecting the quality of the products. This will be avoided by building the walls with refractory materials.

1. Introduction

Heat transfer by convection is a phenomenon of great importance in the industrial sector, in unit operations of the chemical industry [1,2], and indicates the way of heat transfer between a solid surface and an adjacent moving fluid [3]. Existing methods for determining the convective heat transfer coefficient show errors of 15% to 30% [4] due to fluid conditions [5] and surface geometry [6]. To evaluate it, a methodology has been used that consists of applying optimization together with a mathematical model of heat transfer between a fluid and an irregular solid in metal containers, eggs, and conical packages [7,8].

In the municipality of Ocaña, Colombia, the manufacturing of ceramic materials does not have technification in its production processes. These processes do not have temperature, air, and fuel control in the firing process that leads to complete combustion [9], leading to increased fuel consumption, low product quality [10], high production costs, and environmental and health problems due to polluting emissions [11]. The ceramic sector in Ocaña, Colombia, generates a number of direct jobs, becoming one of the main development alternatives for the region [12]. Therefore, it is of great importance to study its processes in order to compete in the current market. At present, there are very few thermal studies in the kilns of the region; studies have been carried out on the drying of bricks [13], mechanical properties of bricks [14], and studies on gas emissions [15]. By 2020, this sector should be the national and binational leader in the field of high-quality ceramic products [12]. To this end, the processes must

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be optimized, and thermal studies of the firing process must be carried out.

This research allows knowing the acquisition of temperatures in different positions inside and outside the kiln, the heat transfer coefficients by convection, and the energy losses in a rectangular intermittent kiln in a forced convection process. This is used for future research in order to optimize the manufacturing processes of ceramic materials.

2. Methodology

The study was carried out in a rectangular intermittent kiln of "Ladrillera el Estanco" located in the municipality of Ocaña, Colombia. The cross section rectangular kiln is 2.5 m long, 2 m wide, 2.88 m high, and wall thickness of 0.35 m. During the firing, a total of 2.200 blocks were produced with a coal consumption of 1.600 kg.

2.1. Design of the virtual temperature acquisition instrument

A virtual instrument was designed and programmed to acquire the faring temperature data in an intermittent kiln. A DAQ assistant software executable of the embedded compact RIO system was used. An NI 9213 I/O data acquisition card assembled on the NI cDAQ-9184 Chassis supported by National instruments was used to process the information received through the installed thermocouples. The program shows on the monitoring screen how the temperature profiles are made for the positions where the thermocouples were placed. At the end of the acquisition process, an excel report is generated of the temperature data recorded and the temperature profiles monitored.

In data acquisition, eight positions were recorded in the kiln, four for internal positions, using K-type aluminum chromium alloy bulb thermocouples with ceramic insulation, which were installed simultaneously with the brick loading process in the kiln. At the remaining four external positions, K-type wire thermocouples with fiberglass coating at 900 °F were used and installed at the same time as the loading door was being closed. The location of the thermocouples was as follows: 1 inner center, 2 interior floors, 3 interior walls, 4 interior gases, 5 exterior centers, 6 exterior floors, 7 exterior walls, and 8 surrounding air, see Figure 1.

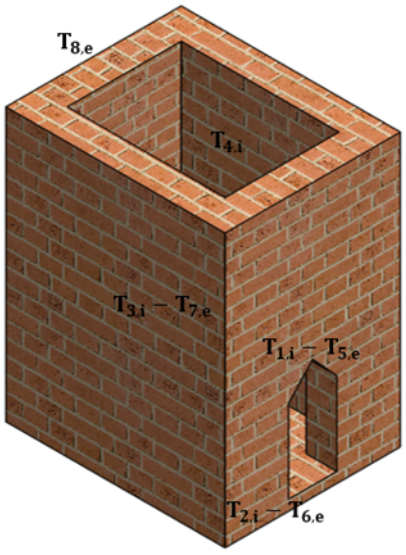


Figure 1. Location of the thermocouples in the intermittent kiln.

2.2. Determination of convective heat transfer coefficients in the kiln

For the evaluation of convective heat transfer coefficients, was determined with the following Equation (1).

$$h = \frac{k\,Nu}{L_C}. \quad (1)$$

Where h is the convective coefficient of the fluid given in (W/m^2 °C), k is the thermal conductivity of the fluid given in (W/m °C), Nu is the Nusselt number, and L_C is the characteristic length of the surface wetted by the fluid given in m. To evaluate the Nusselt number, was determined with the following Equation (2).

$$Nu = 0.68 + \frac{0.670\ Ra^{\frac{1}{4}}}{\left[1+\left(\frac{0.492}{P_r}\right)^{\frac{9}{16}}\right]^{\frac{4}{9}}}. \quad (2)$$

Where Ra is the Rayleigh number and P_r is the Prandtl number. To evaluate the Rayleigh number, was determined with the following Equation (3).

$$Ra = \frac{g\,\beta}{\nu^2}\,\Delta T\,L_C^3 P_r. \quad (3)$$

Where β is the coefficient of thermal expansion of the fluid given in 1/°C, ΔT is the temperature difference between the surface in contact with the fluid given in °C, and ν is the kinematic viscosity of the fluid given in m^2/s.

Using the average temperature of the fluid and the surface, it is calculated the average temperature with which the thermal properties of the fluid will be evaluated (thermal conductivity, coefficient of thermal expansion, Prandtl number, and kinematic viscosity). Based on Newton's law of cooling, the heat flux, was determined with the following Equation (4).

$$Q_{conv} = h\,A_s\,\Delta T. \quad (4)$$

3. Results

The results of the data acquisition, the convective heat transfer coefficient, and the energy loss in the kiln are detailed below.

3.1. Virtual instrument validation

After setting up the temperature acquisition equipment, the virtual instrument was programmed every 5 minutes to record data on the thermocouples installed in the kiln from the beginning of the firing process to the end thereof. The monitoring lasted three days, one hour and 50 minutes. For each position in the kiln, 886 data were recorded for a total of 7.088 data in the firing process. The temperature profiles obtained are shown in Figure 2.

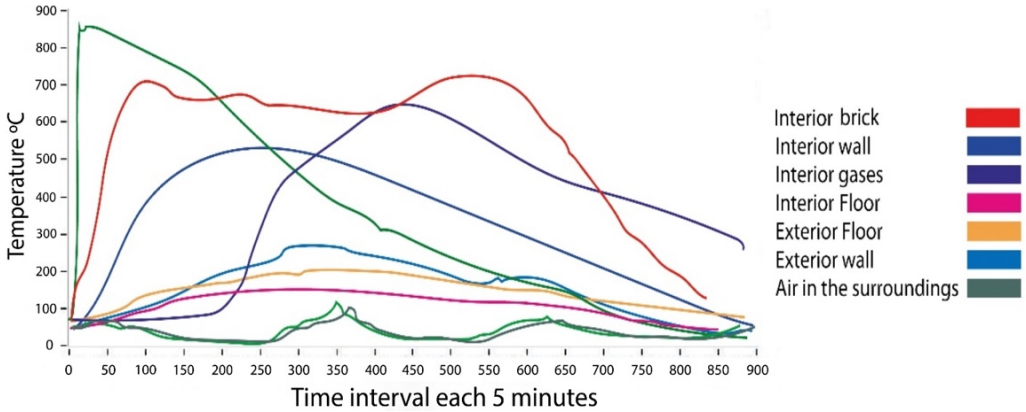


Figure 2. Temperature profiles in intermittent kiln.

The temperature of the combustion gases during the first 18 hours of the firing remained constant at 50 °C. The maximum temperature of 650 °C was reached 35 hours after the start of the firing process due to incomplete combustion of the fuel. At the beginning of the firing curve of the products in the water smoking period, it is observed that the clay did not reach 400 °C, 5 hours after the beginning of the firing. This means that a very slow heating was taking place, extending the water smoking phase, causing an increase in the propagation of water vapor and clay swelling.

In the following 6 hours, the decomposition phase of the organic matter is produced. The curve shows a high heating speed, reaching its maximum slope at 700 °C, causing the pieces to crack on the faces and edges most directly exposed to the fire. The next section of the firing curve is kept constant with an average temperature of 700°C, avoiding differences in shrinkage between the coldest and hottest areas of the products.

The temperature curve on the inner floor in the kiln started with a value close to 50 °C, and as the heating progressed, the floor temperature rose to 200 °C. The maximum and minimum temperatures on the inner and outer walls of the kiln are 500 °C and 200 °C respectively. The temperature difference between the products and the surroundings is associated with the thermal inertia of the parts when heated and cooled at high speed. To determine the convective coefficient of the fluid, it was necessary to collect data from the temperature acquisition on the kiln surfaces obtained with the virtual instrument. Table 1 shows average temperatures, characteristic length, Rayleigh number, Nusselt number, convective coefficient, and heat flux of the four walls and floor of the kiln.

Table 1. Thermodynamic parameters.

Surface	T_{prom} (° K)	Lc (m)	Nu	h ($\frac{W}{m^2 °K}$)	Q_{conv} (W)	Energy losses
Front wall 1	742.59	0.15	20.48	6.34	12219.10	32478367
Back wall	742.59	0.45	45.58	5.44	13539.63	35988336
Right side	742.59	0.56	53.54	5.14	17713.32	4708200
Left side	742.59	0.56	53.54	5.14	17713.32	4708200
Floor	1036.22	0.38	25.13	4.58	5309.09	1411156

The average convective heat transfer coefficient on the furnace walls is 5.52 W/m^2 °C and on the floor is 4.58 W/m^2 °C, while the convective heat transfer on the furnace walls is 61185.37 W and on the floor is 5309.09 W. In the firing process, 1.600 kg of coal were used which provided an available energy of 51.20 kJ. The energy losses on the kiln walls and floor were equivalent to 16.26 kJ and 1.41 kJ respectively. The values of the temperature acquisition of the gases inside the kiln, around 800 °C, are very similar to those found in the research study [16], as are the values of the convective heat transfer coefficient for exhaust gases [16].

4. Conclusions

The data acquisition system using LabView software proved to be a very useful, versatile, and reliable tool in the analysis of the thermal behavior of the kiln since the temperature profiles obtained were very similar to processes in industrial kilns. The temperatures of the exhaust gases in the kiln oscillate around 200 °C, implying great possibilities for waste heat recovery for drying parts, as well as for drying and preheating combustion air. These temperatures are below the 250 °C established for discontinuous furnaces according to article 30 of Resolution 909 and Resolution 802 of 2014 issued by “Ministerio de Ambiente, Vivienda y Desarrollo Territorial, Colombia”. The temperature difference between the base and the top of the batch in the firing chamber is 200 °C and 500 °C respectively. This is a very large difference which makes the firing process unsatisfactory, as the load near the firing chamber can melt and the top of the batch can remain raw.

The higher temperatures were presented in the center of the bricks and therefore the oven accumulates its heat in that position, while on the side walls there are low temperatures, which is why the bricks on that side do not complete their firing process, increasing the cost of the process for products that cannot be sold. The start and end temperatures of the decomposition phase of organic matter are

300 °C and 700 °C respectively. In addition, a high heating rate of 67 °C per hour occurs, causing the cracking of the pieces, which affects the commercial quality standards of the products. The difference in the color of the products was a defect that was observed, which is a determining factor in the quality of the products. This was generated by the lack of uniformity of the temperature inside the kiln, which caused the materials that supported higher temperatures to darken, producing a reddish tone given by the iron oxides.

The energy supplied by the fuel is 51.20 kJ, and the energy losses on the kiln walls are 16.26 kJ, which represents 31.76% of the energy supplied. The energy losses on the kiln floor are 1.41 kJ, which represents 2.75% of the energy supplied. In total, energy losses consume 34.51% of the energy supplied. To reduce heat losses in the kiln, it is necessary to place refractory material throughout the kiln or to increase the thickness of the kiln walls with clay mixture. The minimum value of the heat transfer coefficient is 4.58 W/m^2 °C and is located in the lower part of the furnace where the hearth is located. This is where the heating region begins, where the combustion gases have a longer residence time. Due to the pressure in this zone, the exhaust gases from combustion are dragged into the kiln, producing values of the average heat transfer coefficient on the walls of 5.52 W/m^2 °C.

The heat flux in the walls and floor by convection is 2/3 of the total, which shows the control of the heat exchange process, achieving the energy exchange by convection with the products. As the furnace is not supplied with the theoretical air required for combustion, the fuel used does not burn completely, causing incomplete combustion, which results in the fuel releasing a lower energy rate and producing higher gas emissions into the environment.

In the ceramic sector, some improvements can be easily applied at a low implementation cost. These improvements can be applied to future work that reduces energy consumption, improves product quality, and reduces emissions of polluting gases into the environment with control systems for temperature acquisition and the injection of pulverized coal into the firing process, as well as the reuse of exhaust gases in the drying of the material. In addition, the construction of the chimney would improve the kiln draught and facilitate oxygen for complete combustion and fuel switching to natural gas.

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