Fuel-air ratio required for combustion and analysis of gases in an intermittent kiln

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Abstract. The air-fuel ratio necessary for coal combustion and the study of atmospheric emissions generated in an intermittent kiln of brickworks la Pradera were determined. A mass balance of the coal constituents and an isokinetic sampling of the gas emissions generated in the kiln were carried out. This was done according to the methodology and procedures established by “Ministerio de Ambiente, Vivienda y Desarrollo Territorial” in the protocol for the control and monitoring of atmospheric pollution generated by stationary sources. A combustion gas analyzer was used to measure the concentration of pollutants such as particulate matter, sulfur dioxide, nitrogen oxides, hydrochloric and hydrofluoric acids, and carbon dioxide and monoxide. The average concentrations of particle material, nitrogen oxides, sulfur dioxide, hydrochloric and hydrofluoric acids through the kiln chimney were 1228.60 mg/Nm³, 625.50 mg/Nm³, 563.10 mg/Nm³, 21.50 mg/Nm³ and 6.40 mg/Nm³ respectively, under reference conditions and adjusted to 18% oxygen. The kiln used has energy losses due to incomplete combustion of coal and sensible heat in the flue gases. The concentrations of nitrogen oxides, sulfur dioxides, and particulate matter are above the standard value and do not meet the permissible emission standard. On the other hand, halides do meet the respective standard.

1. Introduction
The progressive increase in the planet temperature, due to global warming, is producing great climate changes that affect the flora and fauna of the planet, as well as generating more drastic events of rains and droughts. The uncontrolled emission of greenhouse gases such as CO₂, derived from the burning of fossil fuels (e.g. oil, gas and coal) is considered by the scientific community to be one of the aggravating factors associated with this increase [1,2]. Particularly, the fossil fuel consumption for energy production in fixed or mobile sources, as well as the deficient control of combustion processes are also considered contributors to this problem [3].

In that context, the ceramic industry in Colombia does not have any technification in its production processes, leading to several processes such as combustion to be deficient and generates environmental and health problems due to its polluting emissions [4], as well as unnecessary costs for companies due to the low quality products which do not comply with the basic quality standards [5]. On the other hand, an inadequate combustion process requires the use of larger amounts of fuel and exposes several factories to the payment of fines by not complying with current environmental regulations [6].

In Ocaña, there are 30 companies in the ceramic industry exclusively dedicated to the production of construction materials such as bricks, blocks and tiles, of which 96.67% are small companies that carry out the coal burning on fixed grid, with an amount of 416280 units corresponding to 40.51% of the total
monthly production in the municipality, while 3.34% correspond to large companies that use continuous kilns with a monthly production of 611320 units that correspond to 59.49% of the production [7].

2. Methodology
The study was carried out in the intermittent kiln of brickworks La Pradera. This research contains the evaluation of the air-fuel ratio necessary for the combustion of coal and the pollutant emissions into the environment established in [8].

2.1. Evaluation of air-fuel ratio
In order to make the air-fuel ratio necessary for the combustion of coal in the intermittent kiln, the emission factors of Colombian fuels listed by “Unidad de Planeación Minero Energética” were taken into account [9].

2.2. Gas measurement procedure
To carry out the study of gas emissions, an eagle combustion analyzer was used, with which the concentration of the pollutants CO, CO2, O2, NO, as well as pressure and temperature of the gases in the chimney were measured directly [10]. Also, a bacharach combustion gas analyzer approved by the United States Environmental Protection Agency (EPA) was used to measure particulate matter, sulfur dioxide and nitrogen oxides, hydrochloric and hydrofluoric acids.

According to the Institute of Hydrology, Meteorology and Environmental Studies, the number of tests or runs for the evaluation of polluting emissions in stationary sources using the method of the combustion analyzer is 3 runs. For each test, 4 measurements were made every 15 minutes. Samples were taken in accordance with the methodology and procedures established in [11]. The methods used to evaluate pollutant emission measurements were: determination of the site, sampling points and location, determination of oxygen and carbon dioxide concentrations in emissions from stationary sources, determination of particle emission, determination of sulfur dioxide concentration, and determination of nitrogen oxide concentration. These methods were adapted to current regulations established by “Ministerio de Ambiente, Vivienda y Desarrollo Territorial” in the protocol for the control and monitoring of air pollution generated by stationary sources [11].

2.2.1. Adjustment to reference conditions. The measurements of the different pollutants were adjusted to reference conditions at 25 °C and pressure of 760 mmHg, as established in [11], using Equation (1).

\[
C_{CR} = C_{CL} \times \left( \frac{T_{CL} \times P_{CR}}{T_{CR} \times P_{CL}} \right)
\] (1)

Where \(C_{CR}\) and \(C_{CL}\) are the pollutant concentrations at reference and local conditions respectively in \((mg/m^3)\). \(T_{CL}\) and \(T_{CR}\) are the temperature of the gases at the exhaust system and at reference conditions in \(°K\). \(P_{CL}\) and \(P_{CR}\) are the pressures of the gases at the exhaust system at reference conditions in \(mm\ Hg\).

Then, the adjustment to oxygen reference conditions of 18% was made, as established in article 88 of the cited resolution, using Equation (2):

\[
C_{CR(O2\ ref)} = C_{CR(X\%)} \times \left( \frac{21.00 - \% O_2\ ref}{21.00 - X \%} \right)
\] (2)

Where \(C_{CR(O2\ ref)}\) and \(C_{CR(X\%)}\) are the concentrations of the pollutant at reference conditions in \((mg/m^3)\), and X % is the oxygen measured at the gas outlet in (%).
3. Results

3.1. Energy and air requirements necessary for combustion

Equation (3) was used for the calculation of the number of moles of carbon, hydrogen, oxygen, nitrogen and sulfur [12]:

\[ N_X = \frac{\text{Percentage of the component in the coal} \times \text{Coal mass (kg)}}{\text{Molecular weight of the component (kg/kmol)}} \] (3)

Table 1 shows the number of moles of the coal elements used in the kiln of brickworks La Pradera.

| Brickworks | Number of moles constituting the coal |
|------------|--------------------------------------|
|            | C   | H₂   | O₂   | N₂   | S   |
| La Pradera | 97.50 | 43.50 | 3.09 | 0.86 | 0.47 |

Equation (4) was used to calculate the balancing coefficients of carbon, hydrogen, sulfur, oxygen, and nitrogen [13]:

\[ 97.50 \times C + 43.50 \times H_2 + 3.09 \times O_2 + 0.86 \times N_2 + 0.47 \times S + a \times (O_2 + 3.76 \times N_2) \rightarrow X \times CO_2 + Y \times H_2O + Z \times SO_2 + W \times N_2 \] (4)

From the mass balance for the constituents, the balancing coefficients for carbon, hydrogen, sulfur, oxygen and nitrogen were obtained, whose values are shown in Table 2.

| Brickworks | Balancing coefficients |
|------------|------------------------|
|            | C   | H₂   | O₂   | N₂   | S   |
| La Pradera | 97.50 | 43.50 | 0.47 | 116.63 | 439.39 |

The balanced of combustion in the kiln of brickworks La Pradera in Equation (5):

\[ 97.50 \times C + 43.50 \times H_2 + 3.09 \times O_2 + 0.86 \times N_2 + 0.47 \times S + 116.63 \times (O_2 + 3.76 \times N_2) \rightarrow 97.50 \times CO_2 + 43.50 \times H_2O + 0.47 \times SO_2 + 439.39 \times N_2 \] (5)

Equation (6) was used for the calculation of the mole fractions of the combustion gases:

\[ N_R = X + Y + Z + W \] (6)

The mole fraction of the gases in the kiln of brickworks La Pradera is 580.86 kmol. Equation (7) was used to calculate the mole fractions of carbon dioxide, water, sulfur, and nitrogen:

\[ Y_X = \frac{\text{Balancing coefficient of each element (kmol)}}{\text{Mole fraction of gases (kmol)}} \] (7)

The mole fractions for carbon dioxide, water, sulfur dioxide, and nitrogen in the brick kiln of brickworks La Pradera are 0.17 kmol, 0.075 kmol, 0.00081 kmol, and 0.76 kmol respectively.

Equation (8) was used to calculate the apparent molar mass of the combustion gases:
\[ M_{ma} = \frac{X \cdot M_{\text{CO}_2} + Y \cdot M_{\text{H}_2\text{O}} + Z \cdot M_{\text{SO}_2} + W \cdot M_{\text{N}_2}}{N_g} \]  

(8)

Where \( M_{ma} \) is the apparent molar mass of the gases in (kg/mol), and \( M_{\text{CO}_2} \), \( M_{\text{H}_2\text{O}} \) and \( M_{\text{N}_2} \) are the molecular weights of carbon dioxide, water, and nitrogen in (kg/mol).

The apparent molar mass of exhaust gases resulting from combustion in the kiln of brickworks La Pradera is 29.97 kg/mol.

Equation (9) was used to calculate the number of moles of air.

\[ N_{\text{air}} = O_2 + 3.76 N_2 \]  

(9)

Equation (10) was used to calculate the air mass.

\[ m_{\text{Air}} = a \cdot N_{\text{air}} \cdot M_{\text{air}} \]  

(10)

Equation (11) was used to calculate the air-fuel mass ratio.

\[ AC = \frac{\text{air mass (kg)}}{\text{fuel mass (kg)}} \]  

(11)

The number of moles of air is 4.76 kmol, the air mass is 16099.61 kg, and the air-fuel mass ratio is 10.73 kg Air/kg Comb in the kiln of brickworks La Pradera. In other words, 10.73 kg of air must be supplied for each kg of coal in the kiln. Table 3 and Table 4 show the concentrations of pollutants.

**Table 3. Concentration of pollutant emissions in brickworks La Pradera.**

| Emission     | O₂ (%) | CO (%) | CO₂ (%) | N₂ (%) |
|--------------|--------|--------|---------|--------|
| Concentration| 10.78  | 3.35   | 9.82    | 76.05  |

**Table 4. Concentration of pollutant emissions in brickworks La Pradera and their comparison with the standard.**

| Parameter                | Units   | Standard | Measured value | Meet the standard |
|--------------------------|---------|----------|----------------|-------------------|
| Particulate matter       | mg/m³   | 250      | 1228.60        | No                |
| Sulfur dioxide           | mg/m³   | 550      | 625.50         | No                |
| Nitrogen oxide           | mg/m³   | 550      | 563.10         | No                |
| Chlorhydric Acid         | mg/m³   | 40       | 21.50          | Yes               |
| Hydrofluoric acid        | mg/m³   | 8        | 6.40           | Yes               |

4. Conclusions

According to the standard, it is established that the temperature of the gases at the exit of the kiln must be below 250 ºC in discontinuous kilns. As the temperature of the gases at the exit of the brick kiln was 66.15 ºC, the parameter established by the standard is met.

The residual heat recovery in the intermittent kiln of brickworks La Pradera is an option that will optimize fuel consumption and mitigate net energy losses in the process. Another aspect to be implemented is the use of hot gases released from the combustion in the dryer.

The result of the gas concentrations emitted at the kiln outlet, was oxygen with a percentage of 12.42%, carbon monoxide with a percentage of 3.01%, carbon dioxide with a percentage of 7.52%, and nitrogen with a percentage of 77.02%.

With the implementation of the air injection system, using an induced draught fan significantly improved the combustion process since the emissions released into the environment decreased.
However, the combustion in the kiln is still incomplete because amounts of carbon monoxide are still present, which may be due to factors in the supply of coal with high ash and moisture content. Therefore, a measure to mitigate environmental pollution is to implement a quality procedure and minimum requirements for the purchase of coal.

The average value of the concentration of nitrogen oxides NOx released into the environment through the kiln flue was 124.60 mg/m$^3$. According to the standard, the admissible emission must be below 550 mg/m$^3$, which indicates compliance with the standard.

The average value of the concentration of sulfur dioxide SO$_2$ released into the environment through the kiln flue was 150.70 mg/m$^3$. According to the standard, the admissible emission must be below 550 mg/m$^3$, which indicates compliance with the standard.

The average value of the concentration of particulate matter released into the environment through the kiln flue was 1056.60 mg/m$^3$. According to the standard, the admissible emission must be below 250 mg/m$^3$, which indicates that there is no compliance with the standard.

With respect to the parameters established by current environmental regulations for emission from stationary sources, brickworks La Pradera does not meet the requirements established by environmental agencies.

The change from fuel to natural gas can allow a reduction in the time of the firing process. The procedure of loading the products in the kiln will be carried out as operators want without the current difficulties since the gas will expand throughout the kiln, providing higher temperature uniformity within the load, reducing energy consumption, improving the quality of the final product, and increasing productivity.

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