Static Model of Cement Rotary Kiln

Modelo Estático de un Horno Rotatorio de Cemento

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Tecno. Lógicas., ISSN 0123-7799, Edición Especial, octubre de 2013, pp. 179-193

Abstract

In this paper, a static model of cement rotary kilns is proposed. The system model is obtained through polynomial series. The proposed model is contrasted with data of a real plant, where optimal results are obtained. Expected results are measured with respect to the clinker production and the combustible consumption is measured in relation with the consumption calorific. The expected result of the approach is the increase of the profitability of the factory through the decrease of the consumption of the combustible.

Keywords

Cement rotatory kiln; static model; MISO systems.

Resumen

En este trabajo, se presenta un modelo estático de un horno rotatorio de cemento. El modelo del sistema se obtiene a través de series de polinomio. El modelo propuesto se verifica con datos reales de la planta, donde se obtuvieron resultados óptimos. Los resultados esperados son medidos con respecto a la producción de Clinker. El consumo de combustible se mide en relación con el consumo calorífico. Los resultados esperados del enfoque es el incremento de los beneficios de la empresa a través de la reducción en el consumo de combustible.

Palabras clave

Horno rotatorio de cemento; modelo estático; sistemas MISO.

1. INTRODUCTION

Cement will remain the key material to satisfy global housing and modern infrastructure needs. As a consequence, the cement industry worldwide is facing growing challenges in conserving material and energy resources, as well as reducing its CO_2 emissions (Schneider et al., 2011). It is postulated that the current warming of the global climate is the result of an increase in anthropogenic greenhouse gas (GHG) emissions, particularly CO_2, since pre-industrial times (Canadell et al., 2007). Global average atmospheric CO_2 has increased from 280 ppm in the 1750 s to 389 ppm in 2010 (Bobicki et al., 2012). Therefore, efforts to reduce the emission of CO_2 are relevant in the current context.

In Latin-American, the cement production is carried out through Cement Rotary Kiln (CRK), principally. The physical properties of the CRK are related directly with the production capacity of the plant. Calcination is a process with high energy consumption, and generates high amount of powder and emission of CO_2. The CRK consumes approximately the 80% of the thermal energy of the cement plant. Therefore, to control the process is necessary to model correctly the CRK.

The modeled of a CRK is hardly task, since the CRK is a multiple input-multiple-output (MIMO) system, which is described as a non-linear system of distributed time-varying parameters (Ortiz et al., 2005; Shahriari et al., 2009). Although, attempts have been made to represent as a linear process with distributed parameters, the techniques more utilized in the last decade are the derived from advanced control as: neuronal network (Stadler et al., 2011; Pani et al., 2013), fuzzy control (Feng et al., 2010; Li, 2010), intelligent control (Yongjian et al., 2006), internal model control (Zhao, et al., 2012) and expert systems (Wang, et al., 2007; Wang et al., 2010). The principal shortcoming is that in these models the stability of the CRK from perturbations is not guaranteed.

In this paper, a static model of a CRK of wet process is presented. The static part, which is obtained from an energy balance represented by heat generated in the combustion of coal and the way that it is distributed throughout the process. For the configuration of the real variables are used data captured from the process control system, which are operated with experimental data and variables that are assumed as constant. The obtained model is validated through the box and whisker diagram.

The paper is organized as follows. Section 2 reviews the clinkerization process. Section 3 presents the static model. The validation of the static model is presented in Section 4. Finally, Section 5 summarizes the main conclusions.

2. CLINKERIZATION PROCESS

Cement consists of three materials, principally: setting regulator (gypsum or anhydrite), additions (limestone, pozzolan or slag) and Clinker. Clinker is formed by calcium silicate which in turn is obtained by partial fusion from a homogeneous mixture of materials containing CaO, SiO_2, Al_2O_3 y Fe_2O_3. The clinkerization process is performed in a CRK with an inclination of 5%. The homogenate material is fed by the upper input; at the bottom is a fuel burner, as it can be seen in Fig. 1. The material is transported into the kiln and when it is near the burner, the temperature of the material increases, allowing the chemical reactions necessary to obtain clinker in the bottom of the kiln.

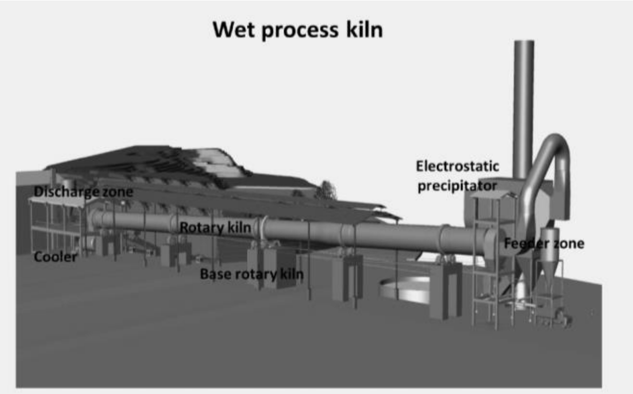

Fig. 1. Basic architecture of a CRK. Source: Cementos Argos S.A.

3. PROPOSED STATIC MODEL

The combustion process is modeled using the principle of adiabatic temperature of flame and the heat utilization factor, exposed in (Marquez Martinez, 1989). The model is obtained using the heat available by the fuel transformation in the process and the various stages in which the heat is used. For instance, in the transformation of the raw material in clinker, the water evaporation and heat loss in the kiln shell. This balance results in the excess heat in the process and that is reflected in the temperature of the flue gases from the furnace.

The development of the model is done by disaggregating (1), which describes the behavior of the heat generated by combustion in terms of the calorific value of the fuel, the fuel enthalpies of combustion air and the energy for the formation of clinker, the losses by convection and radiation and the energy to evaporate the water.

$$\mathrm{H_i + h_c + h_A - Q_{ck} - Q_{RC} - Q_A = M_g C_{pg} \frac{\partial T}{\partial t}} \tag{1}$$

where, H_i is the low calorific power of the combustible, h_c is the fuel enthalpy, h_A is the enthalpy of combustion air, Q_{ck} is the heat of formation of clinker, Q_{RC} is the radiation and convection heat, Q_A is the heat to evaporate water, M_g is the mass of combustion gases, C_{pg} is the flue gas heat capacity and $\frac{\partial T}{\partial t}$ is the temperature change of the exhaust gases. The variables of (1) can be expressed in heat terms, this is made to homogenize the units: the procedure is explained in the following steps:

Step 1. The heat provided by the fuel is a direct relationship between the calorific value and the mass, as it is shown in (2).

$$Q_c = M_c H_C \tag{2}$$

where, Q_c is the Combustion heat or flame, M_c is the fuel mass and H_c is the lower heating value of fuel.

Step 2. The heat or energy of the fuel expressed initially as enthalpy, is given by (3).

$$Q_{ec} = M_c C_{pc}\left(T_{fc} - T_{ic}\right) \tag{3}$$

where, Q_{ec} own heat provided by the fuel, C_{pc} is the fuel heat capacity, T_{fc} is the final temperature of the fuel and T_{ic} is the initial temperature of the fuel.

Step 3. The own heat provided by the combustion of the air is given by (4), this energy is due to preheating of the air used in the combustion.

$$Q_{ea} = M_a C_{pa}\left(T_{fa} - T_{ia}\right) \tag{4}$$

where, Q_{ea} is the own heat provided by the combustion air, M_a is the mass of the combustion air, C_{pa} is the heat capacity of the combustion air, T_{fa} is the final temperature of the combustion air and T_{ia} is the initial temperature of the combustion air.

The air mass (M_a) is obtained from the molar balance of the stoichiometric reaction of the combustion. It is calculated from the amount of oxygen required to oxidize the fuel elemental compounds, such as hydrogen, carbon and sulfur. This reaction is in volume and it is carried out mass by multiplying the density of the air-oxygen ratio, excess oxygen and the fuel mass. The air mass is calculated according to (5).

$$Ma = K_g\left(\frac{C}{P_C} + \frac{H}{P_H} + \frac{S}{P_S}\right)\rho_A R_{AO} E_O M_C \tag{5}$$

where, K_g is the gas constant, C is the percent of carbon in the fuel, H is the percentage of hydrogen in the fuel, S is the percentage of sulfur in the fuel, ρ_A is the density of air, R_{AO} is the ratio of oxygen in the air, E_o is the excess oxygen, finally, P_C, P_H, P_S are the atomic weight of carbon, hydrogen and sulfur, respectively.

Replacing (5) in (4) it is obtained the heat provided by the combustion air in function on the fuel mass as it is shown in (6).

$$Q_{ea} = K_g\left(\frac{C}{P_C} + \frac{H}{P_H} + \frac{S}{P_S}\right)\rho_A R_{AO} E_O M_C C_{pa}\left(T_{fa} - T_{ia}\right) \tag{6}$$

Step 4. The heat required for the clinkerization process is calculated from a chemical balance in which raw materials (previously conditioned) are transformed. This process is based on the energy of formation of the mineralogical compounds present in the clinker, as it is shown in (7).

$$\begin{aligned} Q_{\mathrm{CK}} = (&Q_1P_1(C_aO) + Q_2P_2(Al_2O_3) + Q_3P_3(MgO) + Q_4P_4(SiO_2) \\ &+ Q_5P_5(Fe_2O_3)\,)M_p \end{aligned} \tag{7}$$

where, C_aO is the calcium oxide, Al_2O_3 is the aluminum Oxide, MgO is the magnesium oxide, SiO_2 is the silicon oxide, Fe_2O_3 is the iron oxide, P_i for $i = 1, 2, 3$ is the percentages of the each component, Q_j for $j = 1,2,3$ is the heat of formation of the each component and M_P pasta dough of the feed furnace.

The values of P_i and Q_j are obtained experimentally through laboratory tests. These values are tabulated and depend on kind of clinker that desired manufacture. The chemical composition of the raw material must have the components required for the formation of clinker.

M_p is a mud which consists of solid material and water. Therefore, the main parameters of this material are: humidity, density and the ratio factor between the paste dry basis and clinker. With these parameters is determined the amount of solid material on a dry basis and the amount of water entering the CRK, according to (8).

$$M_P = F_P(1 - h_P\,)K_{PC}\rho_P \tag{8}$$

where, F_P is the volumetric flow of pasta, h_p is the paste humidity, K_{pc} is the factor pasta-clinker and ρ_P is the density of the paste. Equation (9) is obtained from substituting (8) in (7), which expresses the amount of heat necessary to produce a unit quantity of clinker depending on the flow and humidity of the pasta feed to the furnace.

$$Q_{\mathrm{CK}} = (Q_1 P_1 (CaO) + Q_2 P_2 (Al_2 O_3) + Q_3 P_3 (MgO) + Q_4 P_4 (SiO_2) + Q_5 P_5 (Fe_2 O_3)) F_P (1 - h_P) K_{PC} \rho_P \tag{9}$$

Step 5. The CRK is not insulated; therefore, the heat radiation occurs outwards, which results in energy loss for the process. The Q_{RC} term in (1) represent the radiation losses, which can be expressed as

$$Q_{RC} = Q_R + Q_{CV} \tag{10}$$

where, Q_R and Q_{CV} are the losses associated to the radiation and convection, respectively. For this case, Q_R is given by:

$$Q_R = A \mathrm{e} K_B (T_s^4 - T_a^4) \tag{11}$$

where, A is the area of the furnace wall, e is the emissivity, K_B is the Boltzmann constant, T_s is the temperature of the hoof wall, T_a is the ambient temperature. Q_{CV} is given by:

$$Q_{CV} = h_{cv} A (T_s - T_a) \tag{12}$$

where, h_{cv} is the convective coefficient. The total heat loss, according to (10), is given by:

$$Q_{RC} = A \mathrm{e} K_B (T_s^4 - T_a^4) + h_{cv} A (T_s - T_a) \tag{13}$$

Step 6. Water in the clinkerization process appears in two instances. i) Water is present in the feed pulp. For this reason, the amount of water in this part of the process is calculated from the density and the humidity of the paste. The expression used to find the mass of the water that accompanies the pasta feeding the kiln; it is shown in (14). ii) Water is also present in the cooling system, which occurs in the kiln and the steam generated, in this point travels along it. This water is measured as volumetric flow, and using the density becomes in mass, as it is shown in (15).

$$M_{AP} = h_P F_P \rho_P \tag{14}$$

$$M_{AR} = F_A \rho_w \tag{15}$$

where, M_{AP} is the water mass contained in the paste, M_{AR} is the mass water cooling, F_A is the volumetric flow of cooling water and ρ_w is the density of water. The heat used to evaporate water and superheat steam is represented by the term Q_A. Equation (16) shows how to calculate the energy used to evaporate water and superheat steam.

$$Q_A = q_1 + q_2 + q_3 \tag{16}$$

where, Q_A is the heat to evaporate water and superheat steam, q_1 is the heat for heating water of room temperature to boiling temperature (sensible heat), q_2 is the heat for maintaining the boiling temperature (latent heat) and q_3 is the heat for supplying steam from room temperature to superheat temperature (heat of overheating).

The values of q_1, q_2 and q_3 correspond to the equation of state, which does not depend on the trajectory but of the state in each of the intervals of the process. The value of q_1 is the heat required to carry out the water temperature to boiling point at time $t = 0$ to $t = t_1$, q_2 is the heat required to evaporate water from the time t_1 to t_2 and q_3 is the heat required to superheat water vapor above the boiling point. Finally, the total heat Q_A is used throughout the process to evaporate the water that is initially at room temperature and superheat the steam to a temperature resulting desired. Fig. 2 shows that Q_A is not dependent on the path of q_1, q_2 and q_3, but it depend of the each state of the process.

Each component q_1, q_2 and q_3 are represented in (17), (18) and (19), respectively

$$q_1 = k_c M_A (T_E - T_A) \tag{17}$$

$$q_2 = k_e M_A \tag{18}$$

$$q_3 = k_c M_A (T_v - T_e) \tag{19}$$

where, k_c is the heat capacity of water, k_e is the heat capacity of water vapor, T_E is the boiling temperature and T_v is the superheated steam temperature.

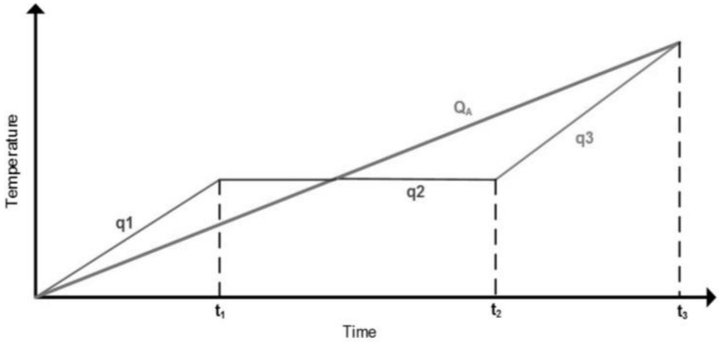

Fig. 2. State diagram of steam. Source: Authors

Equation (20) is obtained replacing (17), (18) and (19) in (16). It is used to calculate the amount of heat required to evaporate water, and to superheat the steam temperature above one hundred degrees.

$$Q_A = k_c M_A (T_E - T_A) + k_e M_A + k_c M_A (T_v - T_e) \tag{20}$$

In the above equation the term M_A is the sum of the amounts of water entering to the kiln by feeding paste and by the cooling system, Eq. (14) and (15), respectively.

Step 7. The right side of (1) is the heat energy carried by the exhaust gas after all the heat energy used in the clinker manufacturing process. These gases are the result from the combustion and their mass depends directly on the amount of fuel became in the process. Therefore, the mass of these gases is calculated by a chemical balance of molar type, similar to that discussed for (5). The expression for calculating the mass of the flue gases is shown in (21).

$$Mg = K_g \left(\frac{C}{P_C} + \frac{H}{P_{H-2}} + \frac{S}{P_S} \right) \rho_G R_{AO} E_O M_C \tag{21}$$

where, ρ_G is the gas density. Equations (2), (3), (6), (9), (13), (20) and (21) are replaced in (1) and it is obtained an expression in terms of mass and volumetric flows, temperatures and excess oxygen. It is to highlight that these are the variables that are measured in the process. The model is implemented in MATLAB / SIMULINK.

4. VALIDATION OF THE STATIC MODEL

In the validation of the model were used data from two different campaigns of the CRK, in the years 2011 and 2012 respectively. It is shown the signals obtained from the model in Fig. 3 and Fig. 4 and the actual signal of the output temperature for data gases in the operation campaigns.

The box and whisker plots of Fig. 5 and Fig. 6 show how the median model signals are closer to the medium of real signals. The whiskers and the ends of the boxes, which represent the difference between the maximum and minimum typical and quartiles of 25% and 75% of the observed data of the actual process and the data predicted by the model.

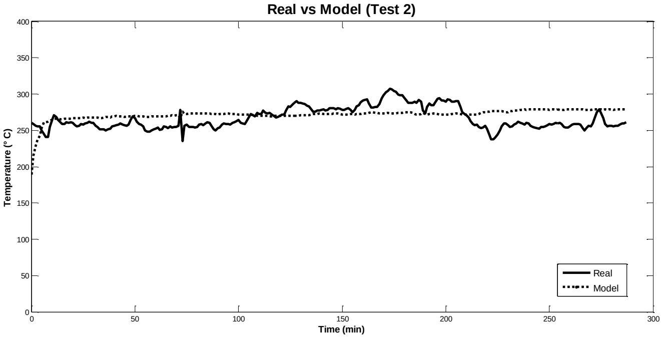

Fig. 3. Real signal vs signal model (Operation 2011). Source: Authors

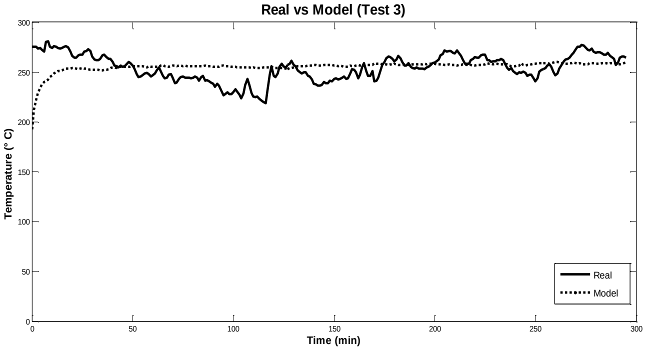

Fig. 4. Real signal vs signal model (Operation 2012). Source: Authors

It can be seen that the whiskers and the ends of the boxes are broader in the actual data that in the data predicted by the model, this is due to noise in the temperature sensor of the process. Values outside the whiskers are outliers that these are not repeated in the model and. These values are associated both with the measured noise of the actual variables of the process and the external perturbations that affect the process.

For this validation, box and whisker plots have been used as a graphical statistical measure to determine the quality of the results obtained. It can be seen, how the medium and lower ends of the boxes decrease for the model data regarding the actual process data. Additionally, it can be observed, a rapprochement between the medium and the whiskers of the model with respect to the actual measurement.

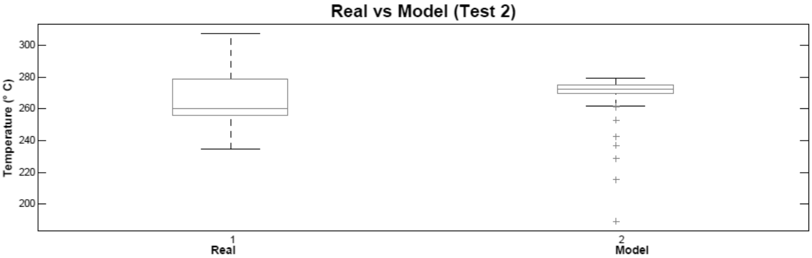

Fig. 5. Boxes and whiskers Test 2. Source: Authors

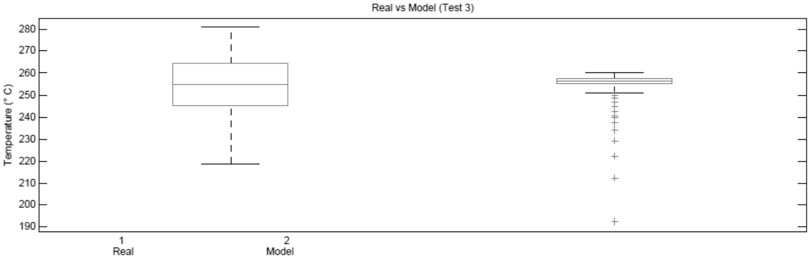

Fig. 6. Boxes and whiskers Test 3. Source: Author

The analysis of the results with statistical methods graphic gives an idea of the behavior of the model data in relation with the data of the actual measure. The principal shortcoming is the difficulty to obtain a quantitative measure of performance to determine the validity of the model.

5. CONCLUSION

This paper has presented a method to model the combustion system of a cement kiln from an energy balance. The method used to measure the performance of the model was the box and whisker plots. The application of this statistical method show the improvements obtained whenever adjustments are applied to the model. Finally, the model presented in this paper, can be used in the design of a robust controller for the CRK, which optimizes fuel consumption and rationalize the dosage of the raw material to help achieve the primary goal. In this way it is possible to reduce CO_2 emissions per ton of fuel and raw materials used in the process of clinkering. The controller design is currently under research.

6. ACKNOWLEDGEMENTS

We thank Cementos Argos SA for allowing the use of databases of white cement process, the engineer John Quiroz for their support and technical advice, the Instituto Tecnológico Metropolitano and Research Group Automatica y Electrónica for their support in the project PM 12104.

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