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Cement Kiln Modeling System Control

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ABSTRACT

Cement kiln is a long cylindrical tunnel, through which cement raw-mix is made to flow in order to be baked, to form clinker. The principle of the baking is based on heat, which is gotten via a burning gas at the front end of the kiln. This work aims at carrying out the mathematical modeling of the temperature in the heating process, in order to improve the efficiency of the kiln control system. The system model was established on the principle of material and heat transfer through data collection. For the model validation, Fuzzy-PID controller was used and compared with Ziegler-Nichols-PID controller. It was seeing that Fuzzy-PID gave a lower overshoot of 9.6% and a settling time of 0.11sec, compared to that of Ziegler-Nichols-PID (ZN-PID), which gave a higher overshoot of 17.24% and a settling time of 0.13sec. For the temperature control, the model gave a better performance in the kiln system operation, using Fuzzy-PID controllers due to its low overshoot and smaller settling time compared to the ZN-PID controllers.

Keywords: Cement Kiln, Baking, Temperature, Hear Transfer, Low Overshoot

Introduction

A rotary kiln is a heat-processing device used to bake material, such as cement raw-mix, to high temperatures. The principle of the baking is based on heat, which is gotten via a burning gas at the front end of the kiln. This work aims at carrying out the mathematical modeling of the temperature in the heating process, in order to improve the efficiency of the kiln control system. The system model was established on the principle of material and heat transfer through data collection. Being non-linear in nature makes its modeling task difficult compared to the linear systems. Basically, some have tried to represent it as a linear process of distributed parameters (Mintus, Hamel, & Krumm, 2006). In this work, Fuzzy tuning of PID was used in the model validation and the result compared with Ziegler-Nichols tuning method; a very useful tuning formula proposed by Ziegler and Nichols in 1942 (Sheel & Gupta, 2012).

Related Review

Karasakal, Yesil¸ Guzelkaya & Eksin, 2005 did a two-input FPID controller that was implemented on a PLC used to control first and second-order systems with dead time formed on a process simulator. The input scaling factor corresponding to the derivative coefficient and the output scaling factor corresponding to the integral coefficient of the two- input FPID controller. These were adjusted using a relative rate observer based tuning method. The relative rate observer method provides a satisfactory response with only one parameter adjustment. For this case, the proportional gain in was kept constant. When two parameters of the controller are tuned, a little better performance at settling time was achieved comparing with one parameter adjustment case.

Han-Xiong, Zhang, Kai-Yuan, & Chen (2005) Based their work on the quantitative model, both theoretical analysis and numerical simulations were carried out to study the fuzzy-PID control with different reasoning methods. It was found that a fuzzy-PID control scheme with different reasoning methods becomes different types of nonlinear PID controllers plus a relay. The optimal fuzzy reasoning method brings in more flexibility in tuning their nonlinear gains, which work better for more complex problems.

He, Tan & Zu (1993) present a fuzzy self-tuning PID control scheme for controlling industrial processes. The essential idea of the scheme is to parameterize the well-known Ziegler-Nichols tuning formula by a single parameter α and then to use an on-line fuzzy inference mechanism to self-tune this parameter. The fuzzy tuning mechanism, with process output error and change of error as inputs, adjusts α in such a way that it speeds up the convergence of the process output to a set point and slows down the divergence trend of the output from the set point. The three PID parameters are related to the single parameter α using also the ultimate gain and the ultimate period extracted from the ZN initialization pre-tuning of the controller prior to its actual use. The form of the parameterization is inspired by the Ziegler-Nichols formula and in fact reduces to it when $\alpha = ½$.

This work laid emphasis on fuzzy-PID controllers in order to overcome the inability of the MPC in its inability to build a non linear model to a low percentage overshoot.

Modeling Method

For the kiln temperature modeling to be carried out, Figure 1 was employed. In its reality, the process variable (heat), is measured by a thermocouple temperature sensing device, which senses the variable heat in the kiln, then fed to the error detector. The set point and measured variable from sensor are compared, to generate an actuating signal to the gas solenoid valve which produces a linear movement of the valve stem to adjust the flow of gas to the burner of the gas fire.

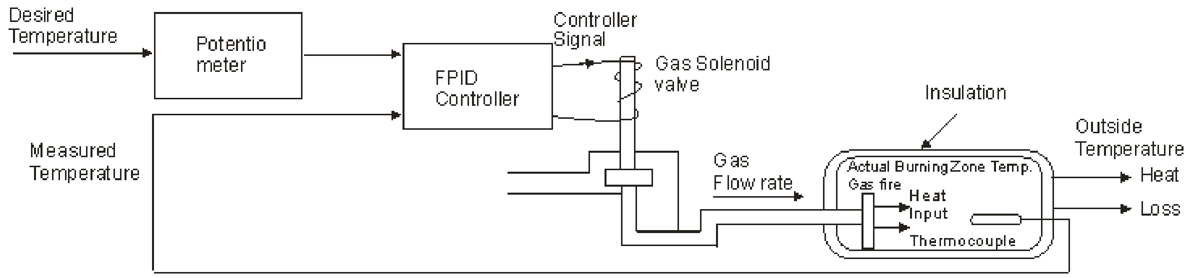


Figure 1: Cement Kiln Heat Control System

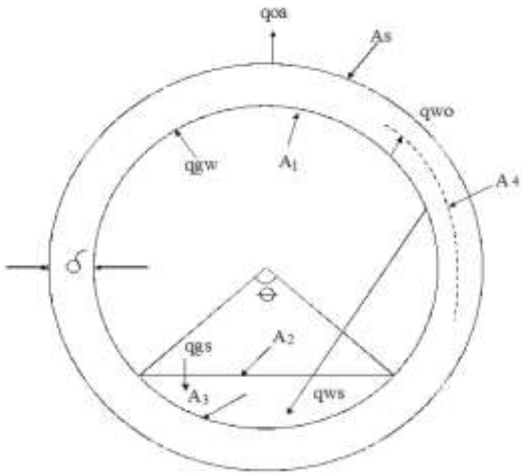


Figure 2: Kiln Thin Slice

From Figure 2 and as presented by Joseph & Olaiya, 2019, the equation of mass and heat balance in solid bed within this thin slice is given as;

$$m_{sm}c_{p,sm}\frac{dT_{sm}}{dz} = Q_{convection\ g\rightarrow eb} + Q_{radiation\ g\rightarrow ew} + Q_{conduction ew\rightarrow eb} + \lambda_{sm}A_{sm}\Delta H_{sm} \quad (1.1)$$

where

m_{sm} = mass flow rate of the solid material, $c_{p,sm}$ = heat capacity of the solid material, J/(kgK) ; T_{sm} = Temperature of the solid material, $°K$, Q = heat transfer rate, λ = production rate for various species, $\mathrm{mol/(m^3.s)}$, ΔH is the enthalpy of reaction, J/mol.

To simplify the differential equation (1.1), the enthalpy of reaction, radiation and convection convection heat are assumed to be neglected. Thus equation 1.1 becomes;

$$m_{sm}c_{p,sm}\frac{dT_{sm}}{dz} = Q_{radiation g\rightarrow eb} \quad (1.2)$$

As presented by Mujumdar, 2006 radiation heat flux in the kiln is given by;

$$Q_{radiation\ g\rightarrow eb} = \sigma A_{g\rightarrow k}(\varepsilon_k + 1)\left[\frac{\varepsilon_g T_g^4 - \alpha_g T_k^4}{2}\right] \quad (1.3)$$

where

k (subscript) = w, s and represents the gas or the solids phase respectively,

σ = Stefan-Boltzmann constant = 11.7x 10^{-8}; A = area of heat transfer = 0.2124m^2 (from Dangote Cement, 2015), ε and α are the emissivity and absorptive of the freeboard gas respectively and T = the temperature. This relation is valid for the radiate heat transfer from gas to solids and walls.

By substituting equation 1.3 into equation 1.2 gives;

$$m_{sm}c_{p,sm}\frac{dT_{sm}}{dz} = Q_{radiationg\rightarrow eb} = \sigma A_{g\rightarrow k}(\varepsilon_k + 1)\left[\frac{\varepsilon_g T_g^4 - \alpha_g T_k^4}{2}\right] \quad (1.4)$$

Equation (1.4) becomes

$$m_{sm}c_{p,sm}\frac{dT_{sm}}{dz} = Q_{radiationg\rightarrow eb} = 11.7x10^{-8} A_{w\rightarrow s}\varepsilon_g \varepsilon_w \Omega(T_w^4 - T_b^4) \quad (1.5)$$

where Ω is the form factor for heat radiated, given by:

$$\Omega = \frac{L_{scl}}{2R(\pi - \xi)} \quad (1.6)$$

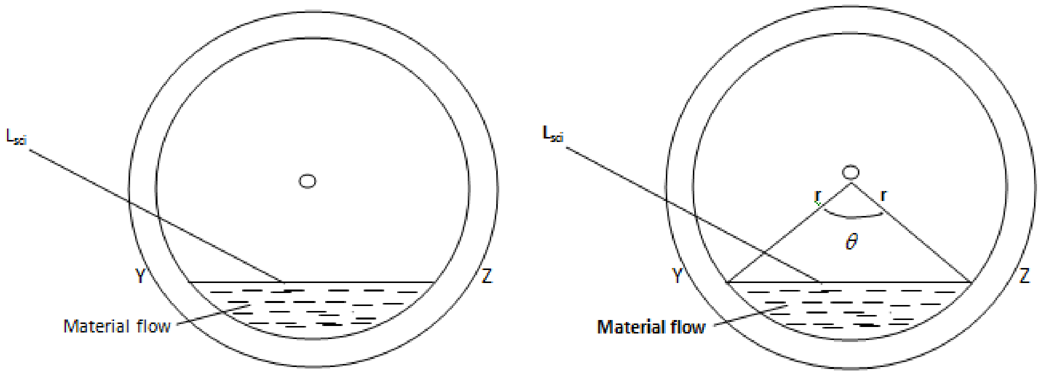
Where

L_{scl} = Chord length from the sector covered by the bed, ξ = dynamic angle of repose a

R = Inner radius of kiln. This radiation model is limited to radiation heat from the uncovered wall to the solids bed and from the free- board to the exposed solids bed.

Lastly, the radiation heat losses from the shell to the environment follows the Stefan Boltzmann Law.

Considering viewing the material flow in Figure 2 from one end of the kiln, in which the material flow is at constant volume (constant height), the outlook is as seeing in Figure 4(a), in which the bed of the material flow forms a chord YZ with centre O. The Chord YZ subtends an angle θ at centre O of the circle, the kiln, by two radii, r, forming triangle YOZ as seeing in Figure 4(b).



(a) (b)

Figure 4: Material flow view in the kiln

Figure 4(b) can be used to determine the length of the chord, L_{scl} as specified by Adu (1998) thus:

$$L_{scl} = 2r\sin(\theta/2) \quad (1.7)$$

Where r = R = Kiln inner diameter; θ = Angle subtends at the centre

Substituting Equation (1.7) into Equation (1.6) gives

$$\Omega = \frac{\sin(\theta/2)}{(\pi - \xi)} \quad (1.8)$$

By substituting Equation (1.8) and area of heat transfer ($A_{w\rightarrow s}$ = 0.2124m^2) into Equation (1.5) gives:

$$m_{sm}c_{p,sm}\frac{dT_{sm}}{dz} = Q_{conductionw\rightarrow eb} = 2.49x10^{-8}\varepsilon_g \varepsilon_w \frac{\sin(\theta/2)}{(\pi - \xi)}(T_w^4 - T_b^4) \quad (1.9)$$

1.3.1 Gas Control Valve/Burner

The transfer function of the gas solenoid valve and burner is given by Dangote Cement, (2015) thus;

$$\frac{Q_i(s)}{E(s)} = \frac{K_v K_b}{T_1 s + 1} \quad (1.10)$$

K_v = valve constant (m^3/sV), K_b = burner constant (Ws/m^3) and $Q_i(s)$ = Heat flow to the material in the kiln.

1.2.2 Transfer Function of the System

The closed-loop transfer function for the temperature control system as seeing from Figure 1 is

$$\frac{\theta_o}{\theta_d} = \frac{\frac{1}{H_1}(T_d T_i s^2 + T_i s + 1)}{\left(\frac{6.24 T_1 T_i}{H_1 K_F}\right)s^3 + \left(\frac{T_i(T_1 + 6.24)}{H_1 K_F} + T_d T_i\right)s^2 + T_i\left(\frac{1}{H_1 K_F} + 1\right)s + 1} \quad (1.11)$$

where $K_F = K_v K_b$

The open-loop transfer function for the temperature control system is;

$$G(s)H(s) = \frac{0.16 K_v K_b}{(1 + T_1 s)(6.24s + 1)(10s + 1)} = \frac{0.4}{(1 + 12\,s)(6.24s + 1)(10s + 1)} \quad (1.12)$$

Mathematical Model Validation

According to the data used in the bed model parameters, the heat transfer mathematical model was validated using a rotary cement kiln, via simulation, to analyze Fuzzy-PID and Ziegler-Nichols-PID (ZN-PID) controllers.

PID Controller Design

PID controller is used in closed loop system to form system control. The output of a PID controller is given by:

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)\,d\tau + T_d\,\frac{de(t)}{dt}\right) \quad (1.13)$$

Where $u(t)$ = input signal to the plant model, $e(t)$ = Error signal, defined as $e(t) = \theta_d(t) - \theta_m(t)$, and $\theta_d(t)$ = desired input heat.

The transfer function of a PID controller is:

$$G_{PID}(s) = \frac{U(s)}{E(s)} = K_p\left(1 + \frac{1}{T_i\,s} + T_d\,s\right) \quad (1.14)$$

$$T_i = K_p / K_i\,; \quad T_d = K_d / K_p$$

where

K_p = proportional gain, T_i = integral and T_d = derivative time constant.

Design of the Fuzzy Logic Control

To design the Fuzzy logic control, three stages are involved, they are; fuzzification, Inference system (knowledge base, data base and inference engine) and de-fuzzification (Bryan and Bryan, 1997). The fuzzification unit converts the crisp data into linguistic format (fuzzy sets). The knowledge base contains the experienced knowledge of the flow process station. Data base contains the membership function and control rules of every linguistic variable, while the inference engine evaluates (process) the fuzzy sets to trigger a rule according to the IF…..THEN rules created in the graphical user interface of the fuzzy logic toolbox in matlab. Finally, the defuzzification unit converts the fuzzy output back to crisp (real output) data (e.g., analog counts) and sends this data to the process via an output module interface. The centroid defuzzification method was used because it provides an accurate result based on the weighted values of several output membership functions.

Auto-Tuning

In this work, simulation of the fuzzy-PID auto-tuning process was done. Tuning the controller gain well gave a better response for the process without overshooting. Thus the controller gave low electrical power consumption. In this regard, for ultimate tuning system for improved system performance, fuzzy logic controller acts as a supervisory organ, to monitor the operation of the PID controller and auto-tune, to eliminate the negative effect of the PID controller.

Result and Discussion of Model

Due to the mathematical model efficiency, it was validated by simulating the temperature of the kiln process based on the heat balance in solid bed within the kiln through convection current. It was seeing from Figure 4 that Fuzzy-PID gave a lower overshoot of 9.6%, a settling time of 0.11sec and a settling temperature of 1450 ºC. Comparing this with the ZN-PID, which gave a higher overshoot of 17.24%, a settling time of 0.13sec and a temperature settling of 1450 ºC as shown in Figure 5, the model showed an improvement in cement rotary kiln control system; in which fuzzy logic controller was used to auto-tune the PID controller; a better tuning method than the ZN-PID, which is mostly used in the industry. This gave better energy/heat consumption, leading to lesser cost.

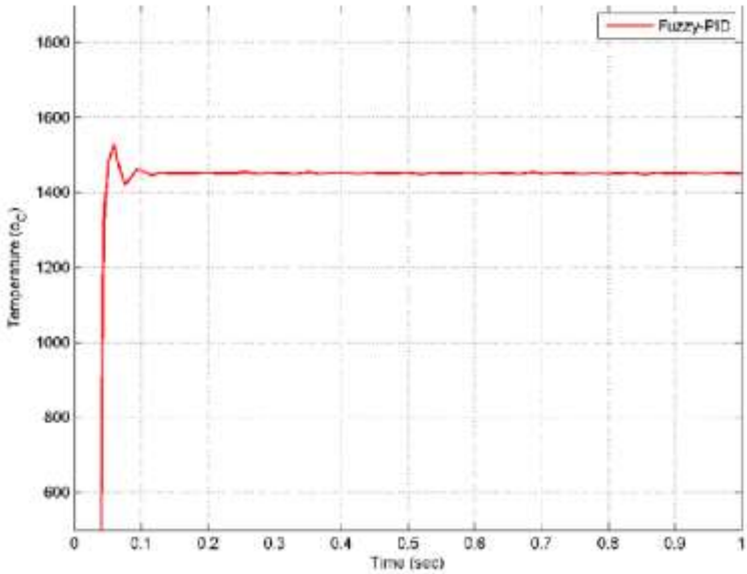


Figure 4: Fuzzy-PID Chart from the Model Simulation

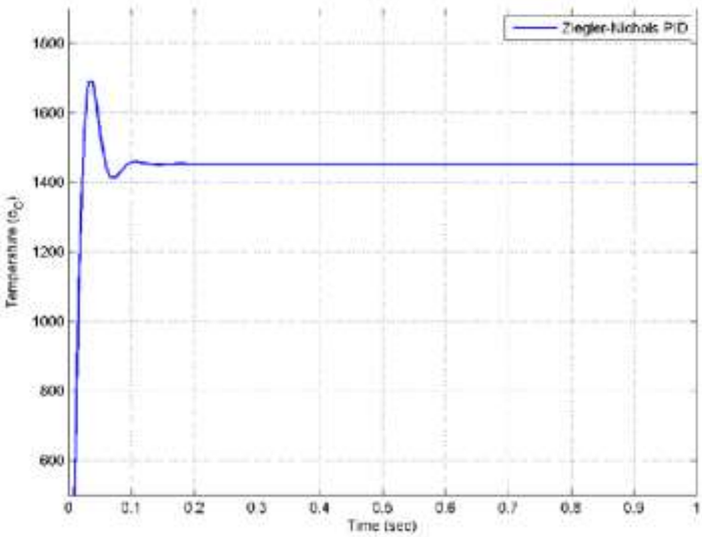


Figure 5: ZN-PID Chart from the Model Simulation

Conclusion

The model gave effective heat transfer to the material in the kiln. This conclusion is as a result of the low settling time, with low overshoot in the Fuzzy-PID but high settling time and high overshoot in the ZN-PID. The model could also be used to evaluate other parameters in the cement process. It was currently used for the evaluation of the temperature control of the cement rotary kiln process, giving a reduced energy consumption and cost in the system. It can be used to effectively solve practical problems that are being faced in the industry, to enable energy conservation and optimum gapn for industry.

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