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Mathematical Model for Heat Control in Rotary Kiln System

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Abstract
Kiln systems are used industrially for processes such as cement production and incineration. This modeling work of the heat control in kiln system was established for further improvement in the kiln control. The system model was established on the principle of mass/heat transfer and on the knowledge of the kinetics of reactions that takes place in the kiln. Data used in the system model was obtained from Dangote cement, Ibese in Nigeria. It was seeing that Fuzzy-PID gave a lower overshoot of 9.6% and a settling time of 0.11sec, compared to that of Cohen-Coon-PID (CC-PID), which gave a higher overshoot of 11.60% and a settling time of 0.129sec. The mathematical modeling gave the better performance for burning zone temperature control of the cement rotary kiln using Fuzzy-PID controllers due to its low overshoot and smaller settling time compared to the CC-PID controllers. This mathematical modeling could be used in cement rotary kiln control system.

Keywords: kiln system, incineration, fuzzy-PID, Cohen-coon-PID, overshoot and modeling

Introduction

Kilns are used in many industrial processes ranging from cement manufacturing to waste incineration (Romero-Valle *et al.*, 2013). While there are many models available within the literature and industry, the wide range of operating conditions justify further modeling work to improve the understanding of the processes taking place within the kiln. However, they are much more widely known for their place in the cement industry as the main stage for the manufacture of cement.

Cement production is a complex process involving a series of activities requiring substantial technological support (Akalp, Dominguez, and Longchamp, 1994). The system model was based on heat transfer in the kiln. Data used in the system model was obtained from Dangote cement, Ibese. A rotary kiln is a pyro-processing device used to raise materials to high temperatures. Being non-linear in nature makes its modeling task is much more difficult compared to the linear systems. Basically, some have tried to represent it as a linear process of distributed parameters (Mintus, Hamel, and Krumm, 2006). In this work, Fuzzy-PID was used in the model validation and the result compared with Cohen-Coon (CC) tuning method; a useful tuning formula proposed by Cohen and Coon (Wang et' al., 1995).

Related Work

Romero-Valle *et al.* (2013) successfully used a CFD empty kiln model was to counteract ring formation in the industrial partner's rotary kiln. The combined model was used to simulate two sets of operating conditions of the kiln process taking into account the unique chemistry of the calcium aluminates. By combining the aspects of the CFD model for the gas phase and a granular bed model for the solid phase, modeling accuracy is improved and by consequence the phenomena occurring in the kiln are better understood.

Hernández et al., (2014) put up a work on the combustion process of a clinker kiln, which is obtained from an energy balance represented in the heat generated by burning coal and how this is distributed across the process. The resulting model is fitted with two tools: least squares and Infinite Impulse Response filter of first order. It validates and verifies the model and its settings using two statistical tools: box and whisker diagram and method of eight statistical metrics related by a fuzzy function. The use of these tools evidence satisfactory performance of the proposed model.

Methodology (The Model)

Figure 1.1 shows how the system heat mathematical model was achieved. The input part of the system, the process variable, is measured by a thermal type resistive thermocouple temperature sensing device, which senses the variable heat in the kiln and is fed to the error detector. The set point and measured variable from sensor are compared and an actuating signal is generated 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. The system operating parameters are as shown in Table 1.1.

The kiln is considered as one-dimensional flow system with its end part being the origin of the coordinates. Taking a differential length, dZ, at any position of the axis of the kiln as shown in Figure 1.2, with consideration of forming an element volume by dZ and the cross section (A_s, A_g) of the kiln, equation of mass and heat balance in solid bed within this thin slice is given as;

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

where

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

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

$$m_{sm}c_{p,sm}\frac{dT_{sm}}{dz} = Q_{convention,\, g\to eb} \qquad (1.2)$$

As presented by Romero-Valle *et al.*, 2013 convection heat flux in the kiln is given by;

$$Q_{convection,\, g\to eb} = \frac{h^c_{g\to sm}A_{g\to sm}}{L_K(T_g - T_{sm})} \qquad (1.3)$$

where L_K is the total kiln length and $A_{g\to sm}$ is the area of heat transfer.

By substituting equation 1.3 into equation 1.2 gives;

$$m_{sm}c_{p,sm}\frac{dT_{sm}}{dz} = Q_{convention,\, g\to eb} = \frac{h^c_{g\to sm}A_{g\to sm}}{L_K(T_g - T_{sm})} \qquad (1.4)$$

$h^c_{g\to sm}$ is the convective heat transfer coefficient from gas to material as given by Mujumdar, 2006 and Li *et al.*, 2005 for a one dimensional Portland Cement Kiln model and is given by;

$$h^c_{g\to sm} = 0.46\frac{k_g}{D_{eq}}\mathrm{Re}_g^{0.535}\mathrm{Re}_w^{0.104}\eta^{-0.341} \; [\mathrm{W.m^{-2}k^{-1}}] \qquad (1.5)$$

where k_g is the gas thermal conductivity and η the kiln load. Re_g and Re_w are the gas phase and angular Reynolds numbers given by:

$$\mathrm{Re}_g = \frac{u_g D_{eq}}{v_g} \quad \text{and} \quad \mathrm{Re}_w = \frac{\omega D_{eq}^2}{v_g} \qquad (1.6)$$

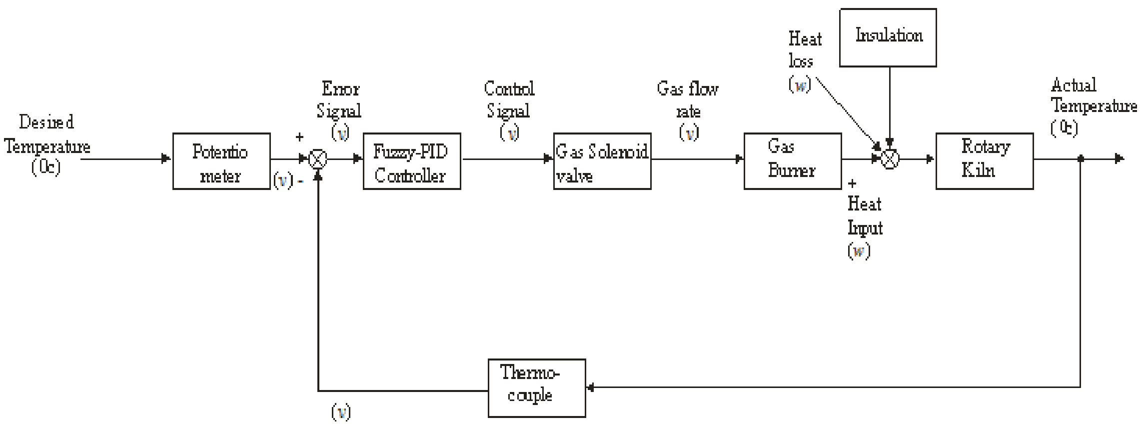

Fig. 1.1: Kiln Heat Control System

Table 1.1: Data used in the bed model validation Source: Dangote PLC, Ibese, 2015

Items	Value
Mass flow rate of the material, m_{sm}	0.017 kg/sec
Specific heat capacity at constant pressure for material, $c_{p.sm}$	1650 kg/m^3

Gas thermal conductivity, k_g	$0.027\ \text{W}/\ °\text{K}$
Internal kiln diameter, D	$0.40\ \text{m}$
Gas velocity, u_g	$2\ \text{m/sec}$
Kinematic viscosity of gas, v_g	$18.84\times 10^{-5}\ \text{m}^2/\text{sec}$
Kiln rotational speed, ω	$1.5 rpm / 0.025 rps$
Kiln load percentage, η	12%
Area of heat transfer, $A_{g\to b}$	$0.2124\ \text{m}^2$
Total length of the kiln, L_K	$5.5\ \text{m}$
Cross sectional half angle due to the kiln fill, φ	$35°$
Product of valve and burner constant, $K_b K_V$	$2.5\ \text{W / V}$
Feedback transfer function of thermocouple, H_1	$0.16/10s+1$
Dissipation time, T_1	$12\ \text{Sec}$
Thermal resistance of the kiln walls, R_T	0.25Ks/J

where u_g is the gas velocity, v_g is the kinematic viscosity of gas, ω is the kiln rotational speed [rad/ s] and D_{eq} represents the equivalent diameter of the kiln given by Li *et al.*, (2005):

$$D_{eq} = \frac{0.5D(2\pi - \varphi + \sin\varphi)}{(\pi - (\varphi/2) + \sin(\varphi/2))} \quad [m] \qquad (1.7)$$

where D is the internal kiln diameter and φ is the cross-sectional half angle due to the kiln fill as shown in Figure 1.2.

By substituting Equation (1.5), (1.6) and (1.7) into Equation (1.4) yields;

$$m_{sm} c_{p,sm} \frac{dT_{sm}}{dz} = Q_{convention,\, g\to eb} = \left[0.46 \frac{k_g}{D_{eq}} \left(\frac{u_g D_{eq}}{v_g} \right)^{0.535} \left(\frac{\omega D_{eq}{}^2}{v_g} \right)^{0.104} \eta^{-0.341} A_{g\to b} \right] \Big/ L_K \left[T_g - T_{sm} \right] \qquad (1.8)$$

Substituting all variable values into Equation 1.8 yields;

$$0.0030 \frac{dT_{sm}}{dz} = T_g - T_{sm} \qquad (1.9)$$

Taking Laplace transforms

$$(0.0030s+1)\, T_{sm}(s) = T_g(s) \qquad (1.10)$$

Gas Control Valve/Burner

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

$$\frac{Q_i(s)}{E(s)} = \frac{K_v K_b}{T_1 s + 1} \qquad (1.11)$$

$K_v =$ valve constant (m^3/sV),

$K_b =$ burner constant (Ws/m^3) and.

$Q_i(s) =$ heat flow to the material in the Kiln

Transfer Function of the System

The complete block diagram of the rotary kiln heat control system as shown in Figure 1.1 gives the closed-loop transfer function for the temperature control system as;

$$\frac{\theta_o}{\theta_d} = \frac{\frac{1}{H_1}(T_d T_i s^2 + T_i s + 1)}{\left(\frac{6.24 T_1 T_i}{H_1 K_F} \right) s^3 + \left(\frac{T_i (T_1 + 6.24)}{H_1 K_F} + T_d T_i \right) s^2 + T_i \left(\frac{1}{H_1 K_F} + 1 \right) s + 1} \qquad (1.12)$$

Where $K_F = K_v K_b$ (1.13)

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

$$G(s)H(s) = \frac{0.16 K_v K_b}{(1 + T_1 s)(6.24s+1)(10s+1)} = \frac{0.4}{(1+12\,s)(6.24s+1)(10s+1)} \qquad (1.14)$$

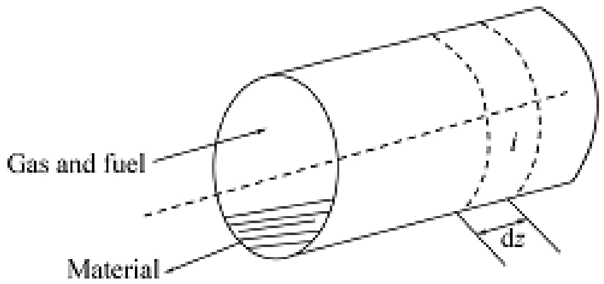

Fig. 1.2: Schematic diagram of gas and material transfer processes of rotary kiln
Source: Yi *et al.*, 2013

System 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 Cohen-Coon-PID (CC-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:

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)\, d\tau + T_d \frac{de(t)}{dt} \right) \quad (1.15)$$

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

The transfer function of a PID controller is:

$$G_{PID}(s) = \frac{U(s)}{E(s)} = K_p\left(1 + \frac{1}{T_i\, s} + T_d\, s\right) \quad (1.16)$$

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

where K_p, T_i and T_d are the proportional gain, integral and the derivative time constant respectively.

Design of Fuzzy Logic Controller

Fuzzy controller is the hardcore unit of the system. It includes the 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.

Membership Function and the Linguistic Variables

Membership function (MF) defines the user-defined charts. The MF used by fuzzy logic controller in this work is the triangular membership function. The input ranges from -6 to +6 and the fuzzy subset are Negative Big, Negative middle, Negative small, Zero, Positive small, Positive middle and Positive Big respectively, with a respective label of NB, NM, NS, ZO, PS, PM, PB. Linguistic Variables (LVs) are variables that can be assigned linguistic terms as values, the LV considered in this work is heat with linguistic terms of Extra low, Very low, Low, Zero, High, Very high and Extra high respectively

Control Rules of the Fuzzy Controller

The control rules are framed to achieve the best performance of the fuzzy controller. In this work forty nine (49) control rules were adopted; this comprises of seven MF for each of the two inputs (error, e and error rate, ė). These rules are as given in Table 1.2, 1.3 and 1.4. Using this control rules flow, fuzzy inference system is created as shown in Figure 1.3. This control rules are framed using the fuzzy logic toolbox available in MATLAB.

Table 1.2: *Kp* Control Rule

Ec / E	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PM	PS	ZO	ZO
NM	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NS
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	PS	ZO	NS	NM	NM	NM	NB
PB	ZO	ZO	NM	NM	NM	NB	NB

Table 1.3: K_i Fuzzy Control Rule

Ec / E	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NM	NM	NS	ZO	ZO
NM	NB	NB	NM	NS	NS	ZO	ZO
NS	NB	NM	NS	NS	ZO	PS	PS
ZO	NM	NM	NS	ZO	PS	PM	PM
PS	NM	NS	ZO	PS	PS	PM	PM
PM	ZO	ZO	PS	PS	PM	PB	PB
PB	ZO	ZO	PS	PM	PM	PB	PB

Table 1.4: K_d Fuzzy Control Rule

Ec / E	NB	NM	NS	ZO	PS	PM	PB
NB	PS	NS	NB	NB	NB	NM	PS
NM	PS	NS	NB	NM	NM	NS	ZO
NS	ZO	NS	NM	NM	NS	NS	ZO
ZO	ZO	NS	NM	NM	NS	NS	ZO
PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
PM	PB	NS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PM	PS	PS	PB

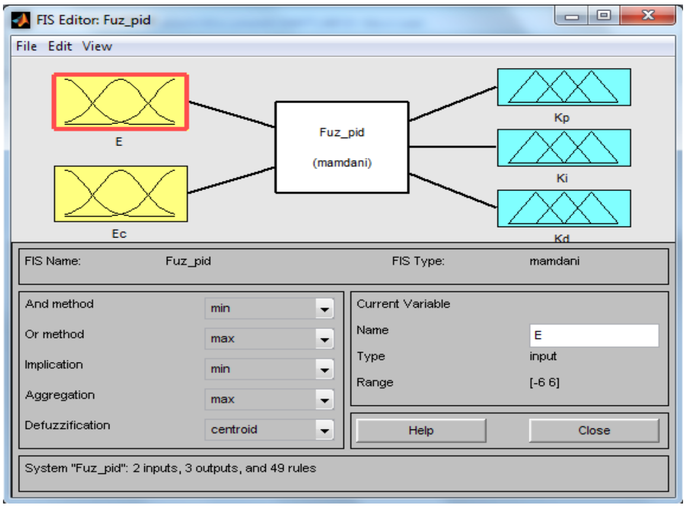

Fig. 1.3: General Fuzzy Logic Controller Based Mamdain-Type Inference System

Fuzzy Self-tuning PID Control Design

The fuzzy logic controller and PID controller are integrated into an adaptive fuzzy-PID controller. The new control system has all the advantages of fuzzy logic control and PID control system. Fig. 1.4 shows the structure of fuzzy-PID controller consisting of two parts namely the conventional PID controller and fuzzy controller.

Auto-Tuning

The simulink diagram showing the simulation of the fuzzy-PID auto-tuning process is shown in Figure 1.5. Since the work was carried out to obtain a better response for the process without overshooting, the controller gain was well tuned. Thus the controller optimizes the power consumption in a process with high electrical consumption. In this regard, to have an ultimate tuning system for improved system performance, fuzzy logic controller will act as a supervisory organ, to monitor the operation of the PID controller and auto-tune in the phase of negative effect from the PID controller.

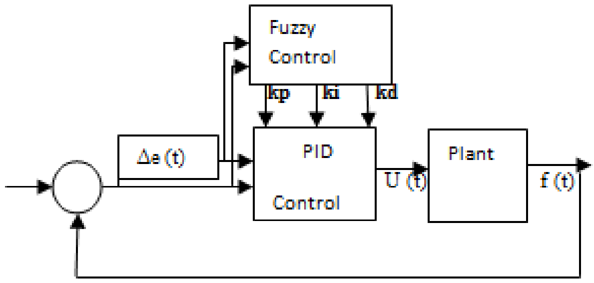

Fig 1.4: Basic structure of plant with control

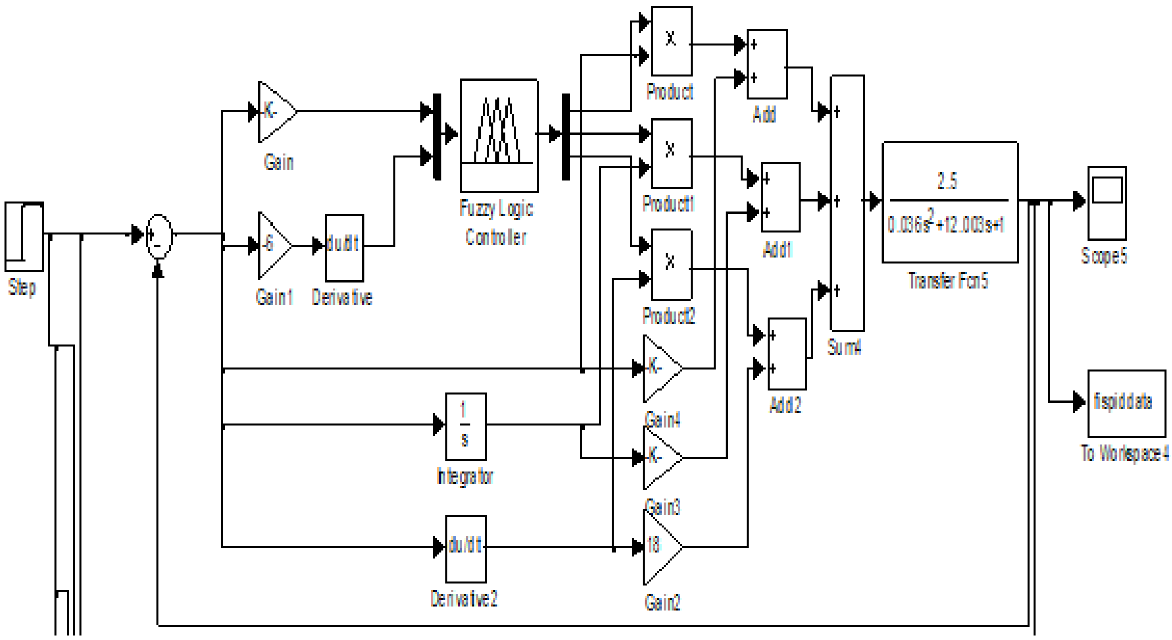

Fig 1.5: Simulink Diagram

Result and Discussion of Model

The model was used to simulate the heat temperature in the kiln process based on the mass and heat balance in solid bed within the kiln. It was seeing that Fuzzy-PID (see Figure 1.6) gave a lower overshoot of 9.6%, a settling time of 0.11sec and a settling temperature of 1450 ^{o}C, compared to that of CC-PID (see Figure 1.7), which gave a higher overshoot of 11.60%, a settling time of 0.129sec and a temperature settling of 1452.1078 ^{o}C. 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.

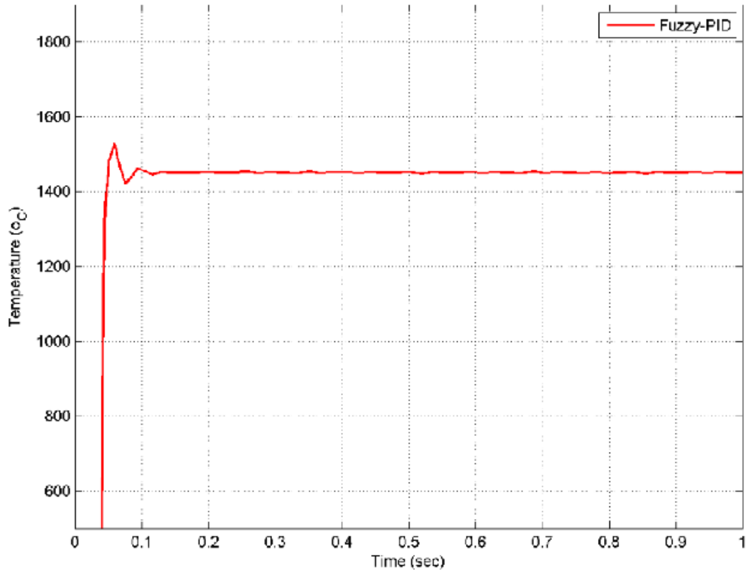

Fig. 1.6: Fuzzy-PID Chart from the Model Simulation

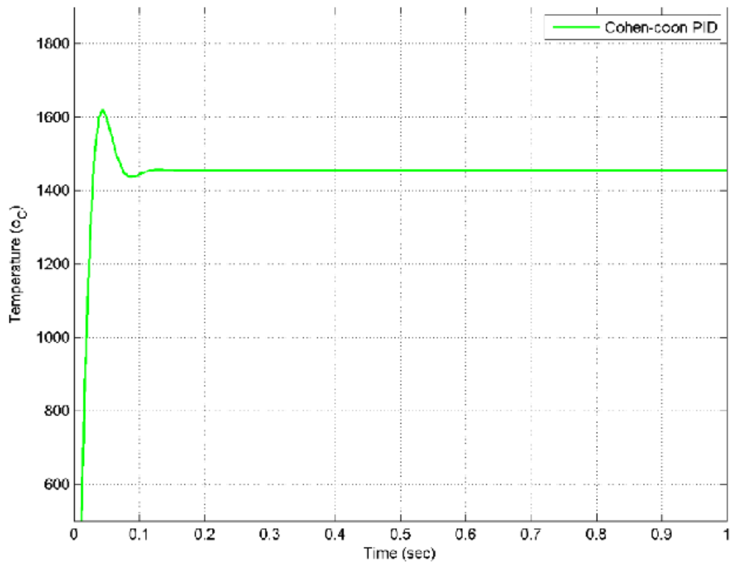

Fig. 1.7: CC-PID Chart from the Model Simulation

Conclusion

The heat mathematical model analyses the heat transfer of the kiln; which shows an effective low settling time, with low overshoot in the Fuzzy-PID, while it has high settling time and high overshoot in the CC-PID. The model could also be used to evaluate other parameters, such as burning zone temperature, pressure in the kiln process. It was currently used for the evaluation of the heat control in kiln process, in order to reduce energy consumption and cost in the system. It can be used to effectively solve practical problems that are being faced in the industry, in order to have energy conservation and consequently to maximize profit for industry.

Contribution to Knowledge

The mathematical model developed shows a better improvement to rotary kiln control in terms of Fuzzy-PID; and reduces the amount of heat wasted by the plant as energy efficiency of plant operation is experienced.

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