Temperature Control System Model for Cement Kiln

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ABSTRACT

The rotary cement kilns have applications in industrial processes. There are many models available within the literature and industrially due to wide operating conditions of the kiln system. This modeling work of the burning zone temperature control of cement rotary kiln was established for further improvement in the kiln control. The system model was established on the principle of material and heat transfer (Pertaining to Stefan-Boltzman theorem). Data used in the system model was obtained from Dangote cement, Ibese and West African Potland Cement, Ewekoro in Nigeria. It was seen 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. 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 ZN-PID controllers. This mathematical modeling could be used in cement rotary kiln control system.

Keywords: Cement, Kiln, Burning, Temperature, Control, Modeling.

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1. INTRODUCTION

Cement rotary kilns are mostly used in 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. 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.

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 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 and Gupta, 2012).

2. LITERATURE REVIEW

Daugherity et al. (1992) describe a self-tuning fuzzy controller where the scaling factors of the inputs are changed in the tuning procedure. The process in which the tuning method was applied was a simple gas-fired water heater, since it is widely used in the petrochemical industry and an accurate simulation model is available. The aim is to replace an existing PID controller with a fuzzy controller, using initial guesses as to the fuzzy membership functions and rules to tune the fuzzy controller for optimum performance and to compare the performance of three control regimes i.e. PID, not- tuned FLC and self-tuning FLC.

A single input/single output process is considered. The FLC has two control inputs: the current error and the change of error. The performance measures for tuning are the overshoot, rise time and the amplitude of oscillation of the transient response of the process. He et al. (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 Ziegler-Nichols 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 $\alpha = \frac{1}{2}$.

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. The use of these tools evidence satisfactory performance of the proposed model. 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.

3. METHODOLOGY (THE MODEL)

In order to realize the system control for burning zone temperature of cement rotary kiln, Figure 1.1 was used. To also realize the modeling aim of this work, a flowchart shown in Figure 1.2 was established. 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.

Taking a differential length, dZ , at any position of the axis of the kiln as in Figure 1.3, with consideration of forming an element volume by dZ and the cross section (A_s , A_g) of the kiln.

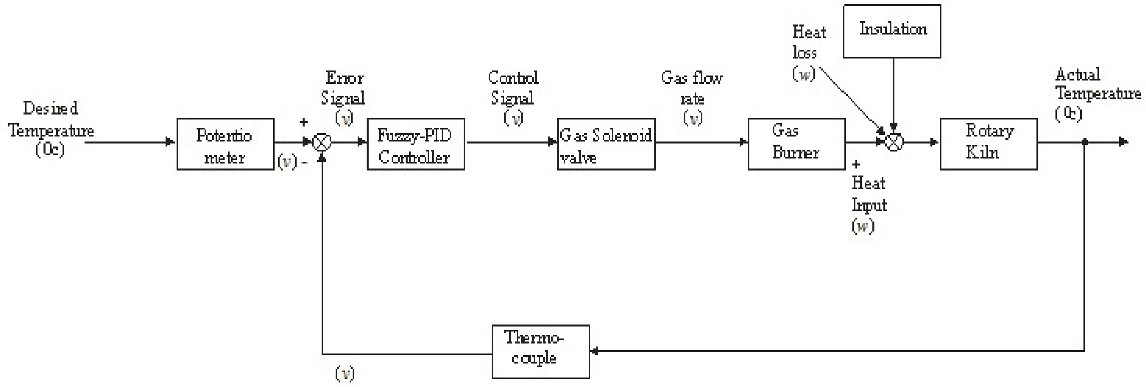


Figure 1.1: Cement Rotary Kiln Burning Zone Heat Control System

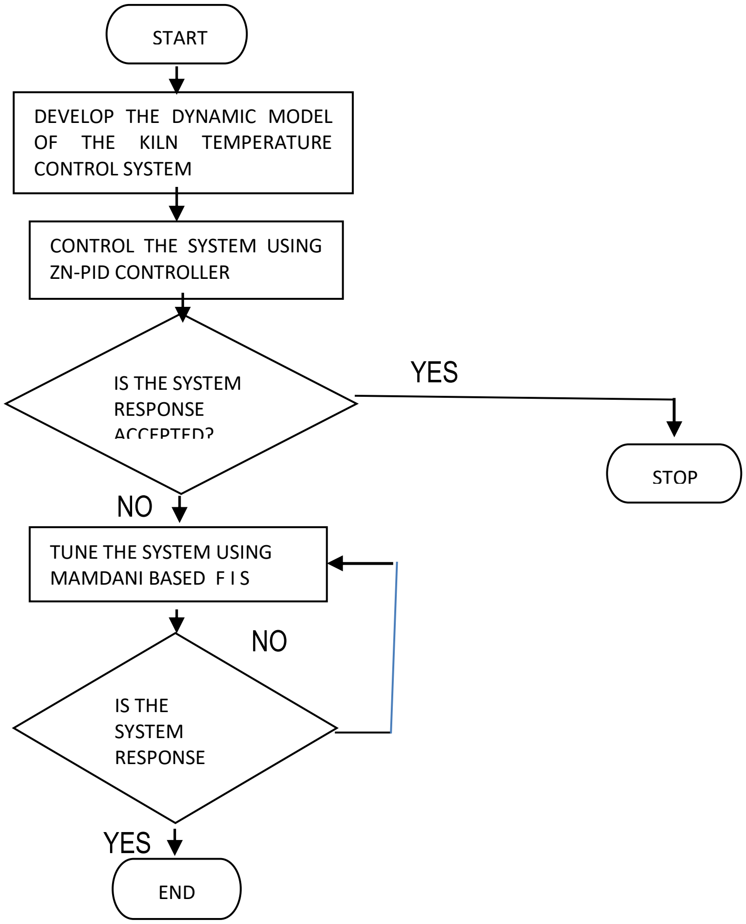


Figure 1.2: Flowchart Diagram for realizing the System Model

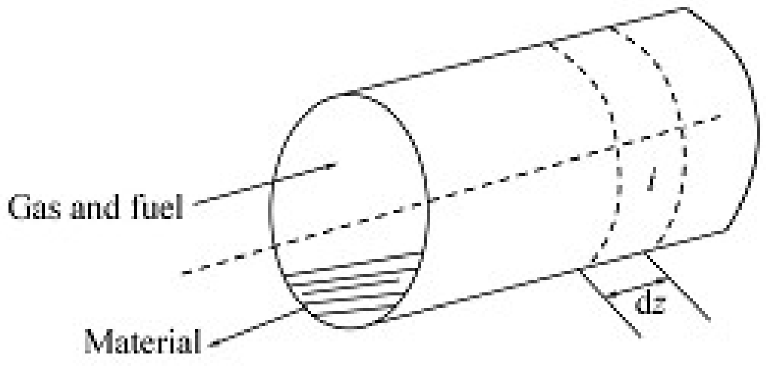


Figure 1.3: Schematic diagram of gas and material flow in rotary kiln
Source: Yi et al., 2013

Equation of mass and heat balance in solid bed within this thin slice (Figure 1.3) is given as;

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

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, $^{\circ}K$, 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, conduction and convection heat are assumed to be neglected. Thus equation 1.1 becomes;

$$m_{sm} c_{p,sm} \frac{dT_{sm}}{dz} = Q_{radiationg\rightarrow eb} \tag{1.2}$$

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

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

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

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

By substituting equation 1.3 into equation 1.2 gives;

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

Equation (1.4) becomes

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

where Ω is the form factor for radiation given by:

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

Where

L_{scl} = length of the chord from the sector covered by the bed, ξ = dynamic angle of repose and R = the kiln inner radius. This radiation model is limited to radiation heat transfer from the uncovered wall to the solids bed and from the free- board to the exposed solids bed.

Lastly, the radiative heat losses from the shell to the environment follows the Stefan

Considering viewing the material flow in Figure 1.3 from one end of the kiln, in which the material flow is at constant volume (constant height), the outlook is as seeing in Figure 1.4(a), in which the bed of the material flow forms a chord AB with centre O. The Chord AB subtends an angle θ at centre O of the circle, the kiln, by two radii, r, forming triangle AOB as seeing in Figure 1.4(b).

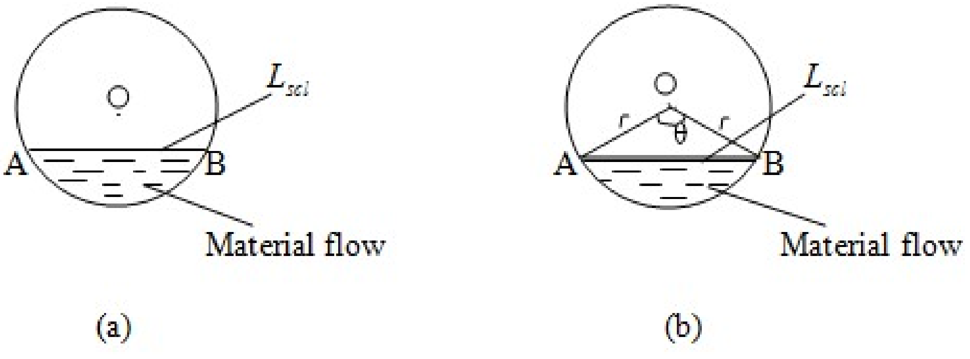


Figure 1.4: View of Material Flow

Figure 1.4(b) can be used to determine the length of the chord, L_{scl} as specified by Adu (1998) thus:

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

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

Substituting Equation (1.7) into Equation (1.6) gives

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

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

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

3.1 Gas Control Valve/Burner

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

$$\frac{Q_i(s)}{E(s)} = \frac{K_vK_b}{T_1s+1} \tag{1.10}$$

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

3.2. Transfer Function of the System

The closed-loop transfer function for the temperature control system as seeing from Figure 1.1 is

$$\frac{\theta_o}{\theta_d} = \frac{\frac{1}{H_1}(T_dT_is^2 + T_is + 1)}{\left(\frac{6.24T_1T_i}{H_1K_F}\right)s^3 + \left(\frac{T_i(T_1+6.24)}{H_1K_F} + T_dT_i\right)s^2 + T_i\left(\frac{1}{H_1K_F}+1\right)s + 1} \tag{1.11}$$

where $K_F = K_vK_b$

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

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

3.4 Developed 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.

3.4.1 PID Controller Design

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

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

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:

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

$$T_i = K_p / K_i\,, \quad T_d = K_d / K_p \qquad (1.14)$$

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

3.4.2 FLC Design

The design of FLC system 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.

The membership function (MF) used by the FLC in this work is the triangular membership function, with input range of -6 to +6 and fuzzy subset of Negative Big (NB), Negative Middle (NM), Negative Small (NS), Zero (ZO), Positive Small (PS), Positive Middle (PM) and Positive Big (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

3.4.2.1 Control Rules of the Fuzzy Controller

Forty nine (49) control rules were adopted in this to have the best output; 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 (Mamdani-type), shown in Figure 1.5. This control rules are framed using the fuzzy logic toolbox available in MATLAB.

Table 1.2: Kp **Control Rule**

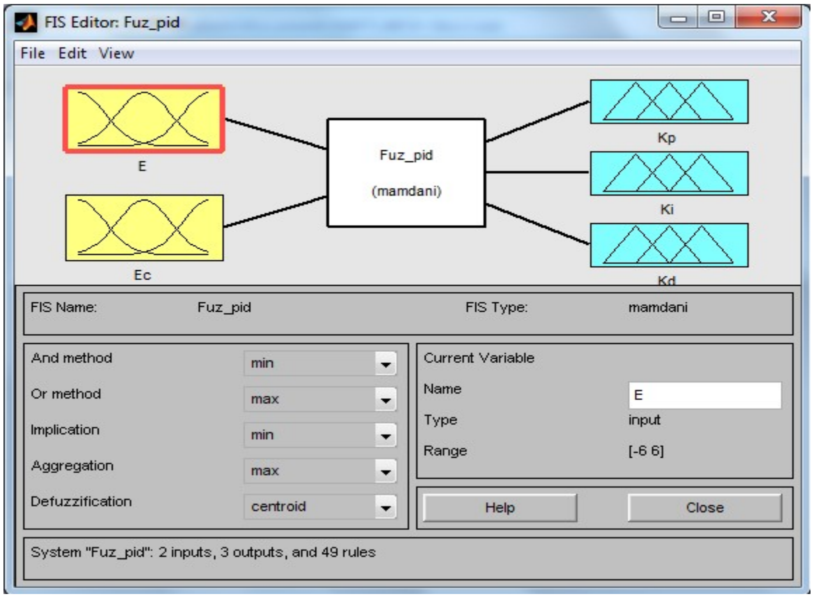
EC / **E**	**NB**	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
NB	PB	PB	PM	PM	PS	ZO	ZO
NM	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NS
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	PS	ZO	NS	NM	NM	NM	NB
PB	ZO	ZO	NM	NM	NM	NB	NB

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	PB
PM	ZO	ZO	PS	PS	PM	PB	PB
PB	ZO	ZO	PS	PM	PM	PB	PB

Table 1.4: K_d Fuzzy Control Rule

E \ EC	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	NS	NS	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



FIS Name: Fuz_pid
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid
Current Variable
Name: E
Type: input
Range: [-6 6]
System "Fuz_pid": 2 inputs, 3 outputs, and 49 rules

Figure 1.5: General Fuzzy Logic Controller Based Mamdain-Type Inference System

3.4.2.3 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. Figure 1.6 shows the structure of fuzzy-PID controller consisting of two parts namely the conventional PID controller and fuzzy controller.

4. AUTO-TUNING

The simulink diagram showing the simulation of the fuzzy-PID auto-tuning process is shown in Figure 1.7. 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.

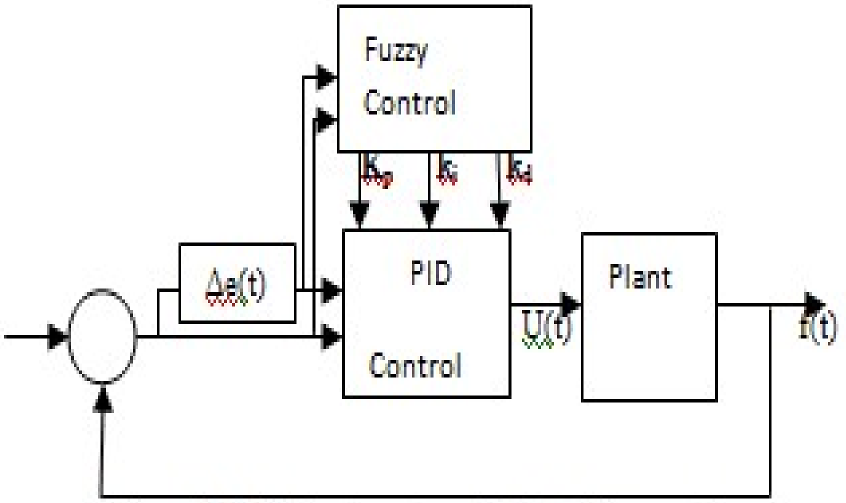


Figure 1.6: Basic structure of plant with control

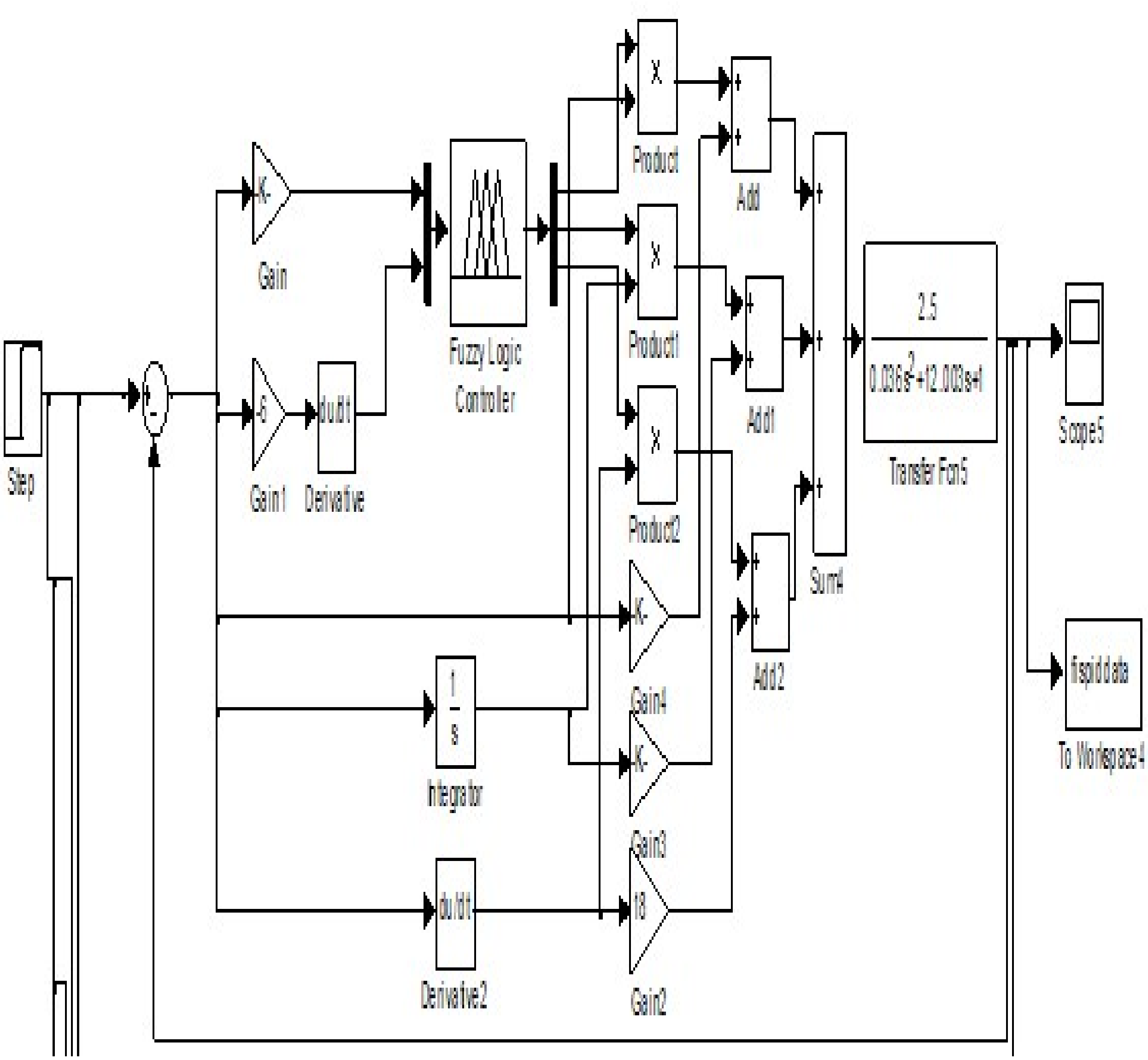


Figure 1.7: Simulink Diagram

5. RESULT AND DISCUSSION OF MODEL

The model was used to simulate the burning zone temperature of the kiln process based on the mass and heat balance in solid bed within the kiln. The analysis was based on the proposed algorithm in Figure 1.2. It was seeing from Figure 1.8 that Fuzzy-PID 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 ZN-PID, which gave a higher overshoot of 17.24%, a settling time of 0.13sec and a temperature settling of 1450 ^{o}C as shown in Figure 1.9. 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.

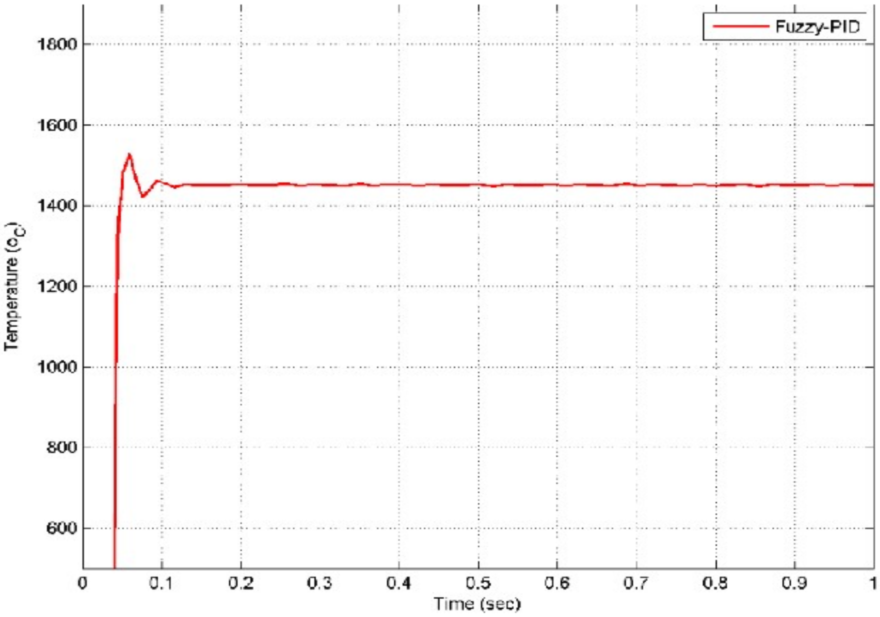


Figure 1.8: Fuzzy-PID Chart from the Model Simulation

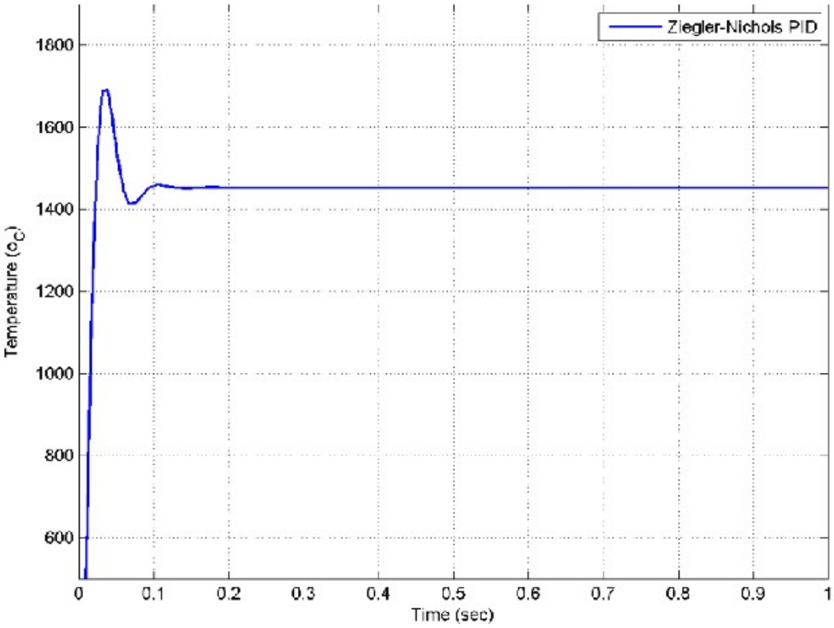


Figure 1.9: ZN-PID Chart from the Model Simulation

6. CONCLUSION

The model effectively explains the behavior of the burning zone heat transfer of cement rotary kiln. It gives a low settling time, with low overshoot in the Fuzzy-PID, while it has 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 burning zone temperature of the cement rotary 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.

7. CONTRIBUTION TO KNOWLEDGE

The developed model shows a better improvement in rotary kiln control in terms of Fuzzy-PID; leading to cost effectiveness in the system.

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