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Multivariable Controller Design for Lime Kiln Process

Sandeep Kumar Sunori[*] and Pradeep Kumar Juneja[**]

Abstract: Lime kiln is an important industrial process in many chemical industries. From control system perspective it offers a challenge, as it is multivariable, interactive, complex and delayed process. In present analysis, multivariable lime kiln process is selected with high multivariable interaction. In its transfer function, there are two manipulated variables namely the fuel gas flowrate, and the percent opening of the induced draft damper and two controlled variables namely front end temperature and back end temperature. RGA analysis and Niederlinski index is analyzed for its interaction and stability consideration respectively. Also controllers designed based on conventional PID technique and fuzzy logic are compared for their performance. The decoupling of this system is performed and the closed loop step responses are compared with those of the composite MIMO system.

Key words: Multivariable control, Decoupler design, lime kiln, fuzzy logic control, PID control

1. INTRODUCTION

Limekiln is essentially a long rotating cylinder with single or two layer refractory and insulation inside the kiln and is slightly inclined to the horizontal as shown in Fig. 1. The task of the kiln is to convert lime mud (CaCO3) into lime (CaO) by the calcination process. This conversion process is endothermic, requiring large amount of heat to be supplied to the kiln. The chemical equation of this reaction is[1]:

CaCO3 + heat —.> CaO + CO2.

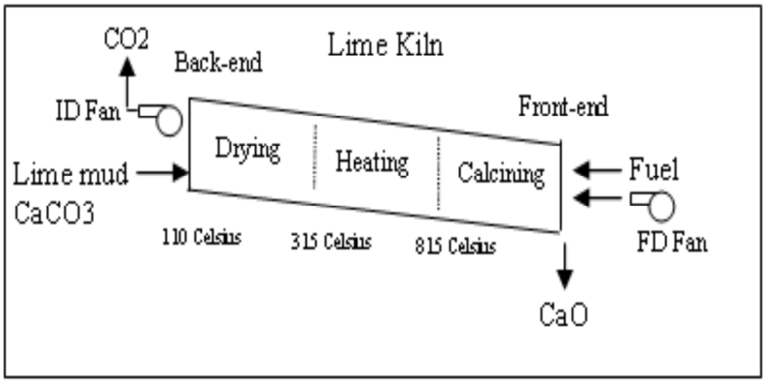

Figure 1: Lime kiln process [1]

The entire lime kiln can be divided into three temperature zones namely the drying section where the wet lime mud is dried at temperature 230 Fahrenheit, the heating section where mud powder is heated up to temperature 600 Fahrenheit and the calcination section where the lime mud is converted to lime.This reaction takes place at temperature 1500 Fahrenheit.The measure of the lime quality is the amount of residual carbon dioxide in the resulting CaO.

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[*] Department of Electronics and Communication Engineering, Graphic Era Hill University, Bhimtal Campus

[**] School of Engineering & Technology, Graphic Era University, Dehradun

A fuzzy MPC technique was proposed for distillation column which is a complex nonlinear multivariable process [2]. The performance was reported to be better than that of conventional controllers. Micha³ Rogalewicz *et al.* used statistical methods to control manufacturing processes and compared univariate SPC with multivariate SPC[3].

Multivariate statistical process control (MSPC) and engg. Process control (EPC) were reported to be the two complementary techniques in the field of process control. EPC nullifies the impact of disturbance. SPC diagnoses the reasons of variations and removes them [4].

Particle swarm optimization (PSO) algorithm was used to design PID controller for a fuzzy model.PSO –PID controller was compared with ZN (Ziegler-Nicholes)-PID controller. The reduction in the overshoot was reported in the former as compared to the latter [5].

P. Naidoo *et al.* set up communication between the control system and the process field devices using profibus-PA and profibus-DP.A PLC was used to control the plant [6].

A control strategy was developed to control a continuous polymerization reactor and its performance was evaluated using simulations [7]. Dan Altena *et al.* applied advanced multivariable control on a natural gas plant and its performance was compared with the conventional feedback controllers. This paper also focused on control strategy for complex turbo expander process [8].

Dynamic matrix control (DMC) scheme was used for a drum boiler turbine. An intelligence based decision mechanism (IBDM) was implemented which supported both model approach and control scheme [9]. R. Hanuma Naik *et al.* [10] developed decentralized controller for multivariable process based on RGA and Neiderlinski index analysis.An algorithm was developed by integration of multi resolution analysis (MRA) and principal curves (PC) for controlling multivariable processes [11].

2. PLANT MODEL AND ITS MULTIVARIABLE ANALYSIS

In the present work two temperatures are controlled in the kiln,the front-end temperature (Tfe), and the backend temperature (Tbe). The process has two manipulated variables: the fuel gas flowrate (F), and the percent opening of the induced draft damper (vp). Equation 1 shows the model of an industrial lime kiln (developed from mill tests) that will be used to design the controller.

$$\begin{bmatrix} T_{fe} \\ T_{bs} \end{bmatrix} = \begin{bmatrix} \dfrac{0.6}{3s+1} & \dfrac{-2.1}{(6s+1)(5s+1)} \\ \dfrac{0.1}{(10s+1)(s+1)} & \dfrac{0.9}{(7s+1)(10s+1)} \end{bmatrix} \begin{bmatrix} F \\ vp \end{bmatrix} \tag{1}$$

The open loop step response of this plant model is shown in Fig. 2.

Before designing the multiloop controller for the considered plant the suitable pairing between manipulated and control variables is done by determining the relative gain array (RGA) [14].

Consider the steady state model of a 2x2 MIMO plant,

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{2}$$

Where u_1, u_2 are manipulated variables and y_1, y_2 are controlled variables. The steady state gain matrix is given by,

$$[K] = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \tag{3}$$

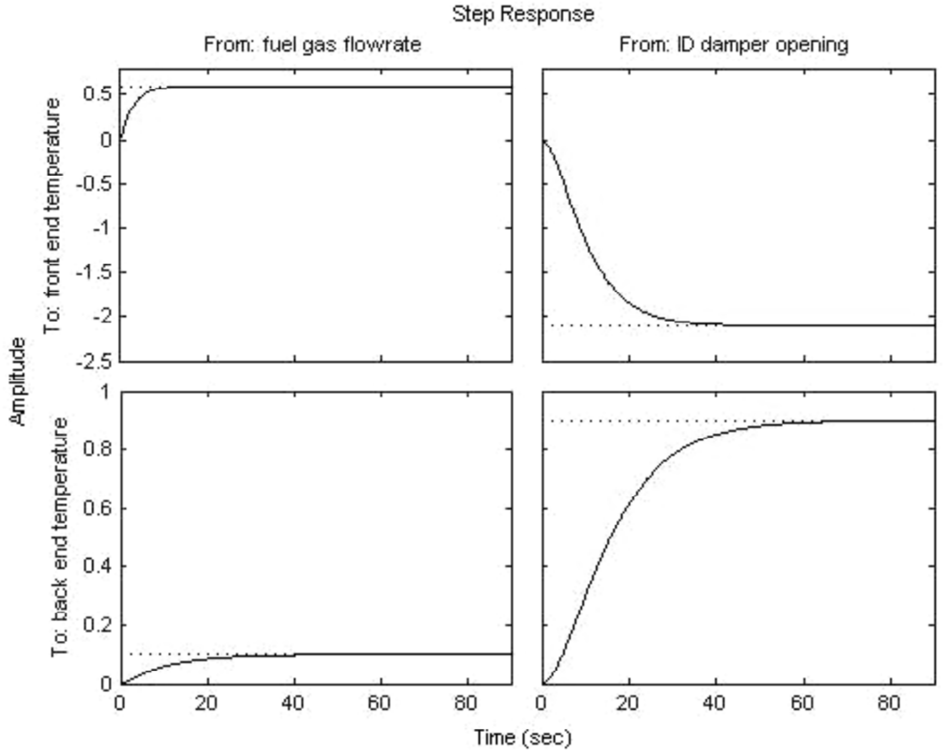

Figure 2: Open loop step response

Now the RGA is expressed as:

$$RGA = \begin{bmatrix} \lambda_{11} & \lambda_{12} \\ \lambda_{21} & \lambda_{22} \end{bmatrix} \tag{4}$$

Where $\lambda_{12} = \lambda_{21} = 1-\lambda_{11}$ and $\lambda_{22} = \lambda_{11}$ and,

$$\lambda_{11} = \frac{1}{1 - \dfrac{K_{12}K_{21}}{K_{11}K_{22}}} \tag{5}$$

If $\lambda_{12} < \lambda_{11}$ then suitable pairing is u_1-y_1 and u_2-y_2 else it is u_1-y_2 and u_2-$y_{1..}$

Using relations (2) - (5) lets find out RGA for the considered plant.For this plant the steady state gain matrix is given below,

$$[K] = \begin{bmatrix} 0.6 & -2.1 \\ 0.1 & 0.9 \end{bmatrix} \tag{6}$$

Using relations (4), (5) and (6), the RGA is determined as,

$$RGA = \begin{bmatrix} 0.72 & 0.28 \\ 0.28 & 0.72 \end{bmatrix} \tag{7}$$

This RGA suggests that the suitable pairing is u_1-y_1 and u_2-$y_{2.}$

The second parameter is the Niederlinski index [12] which determines the closed loop stability of the control system. It is calculated using the following relation

$$N = \frac{Det[K]}{K_{11}K_{22}} \tag{8}$$

The MIMO system will be unstable for all possible values of controller parameters if N < 0 [12]

Now using relation (8), the Neiderlinski index for this plant is determined as,

$$N = \frac{\begin{vmatrix} 0.6 & -2.1 \\ 0.1 & 0.9 \end{vmatrix}}{0.6 \times 0.9} = 1.38 \tag{9}$$

Hence for this plant N > 0 which indicates that the system is closed loop stable.

3. MULTILOOP PI CONTROLLER DESIGN

The SIMULINK model of multiloop PI controller for the considered lime kiln plant is depicted in Fig.3 with tuned values $K_p = 0.144$ and $K_i = 0.205$ for controller1 and $K_p = 1.591$ and $K_i = 0.070$ for controller 2. The corresponding front end temperature and back end temperature responses are presented in Fig. 4 and 5.The characterstic parameters of these responses are specified in Table 1 and 2.

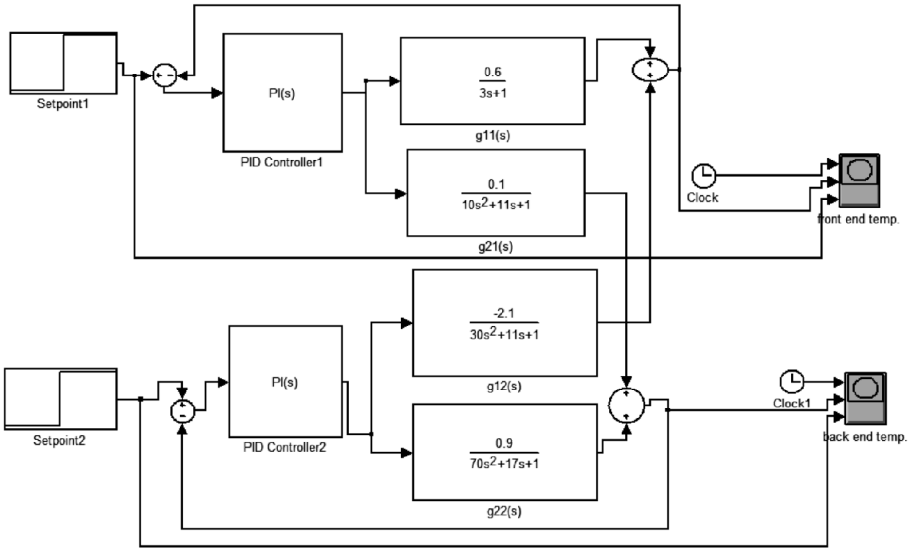

Figure 3: Simulink model of multiloop PI controller

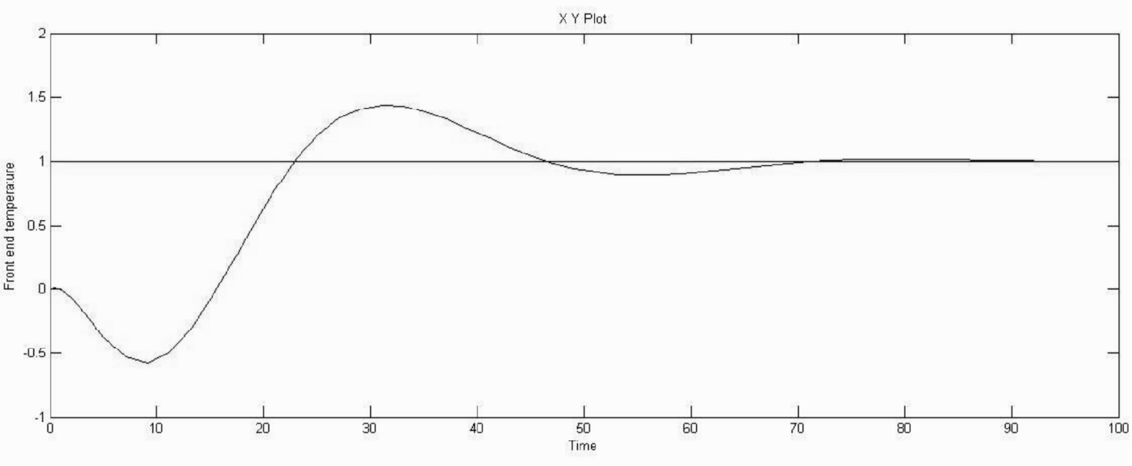

Figure 4: Front end temperature response of PI controller

Table 1
Characterstics of front end temperature response of PI controller

Parameter	*Value*
Rise time (sec)	11.7
Setteling time (sec)	70
Overshoot (%)	10.5
Peak amplitude	1.11

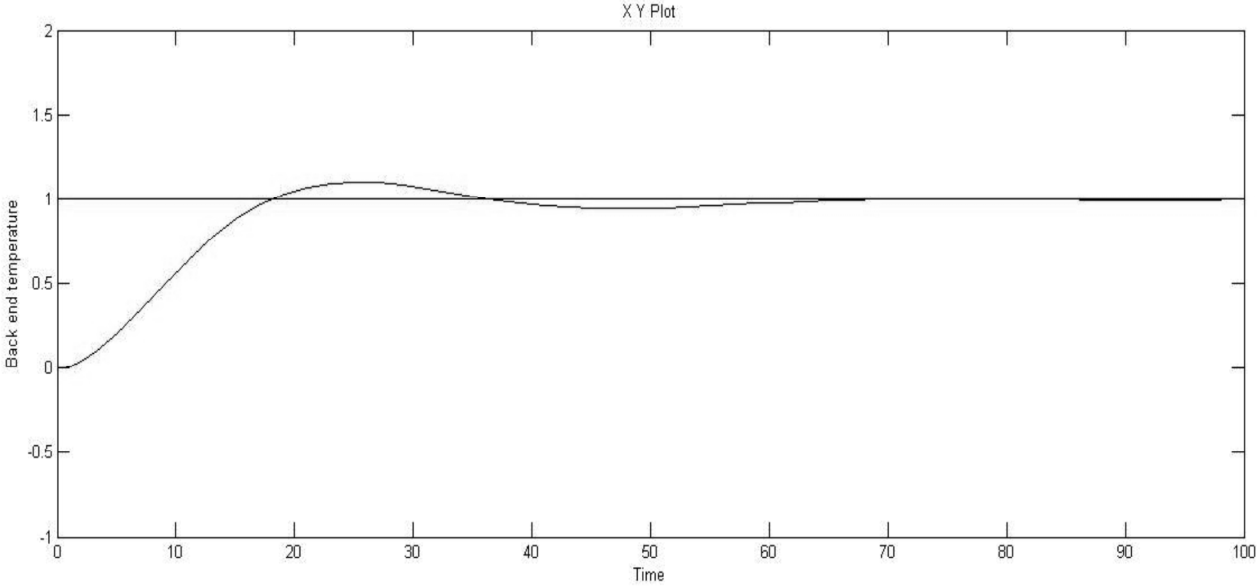

Figure 5: Back end temperature response of PI controller

Table 2
Characterstics of back end temperature response of PI controller

Parameter	*Value*
Rise time (sec)	13.6
Setteling time (sec)	64.8
Overshoot (%)	5.5
Peak amplitude	1.05

4. FUZZY LOGIC CONTROLLER DESIGN

The SIMULINK model of fuzzy logic controller is shown in Fig. 6. The two inputs to the fuzzy controller are FET ERROR and BET ERROR and the two outputs are FUEL FLOW RATE and ID OPENING. Seven linguistic variables NL (nagative large), NM (negative medium), NS (negative small), Z (zero), PS (positive small), PM (positive medium) and PL (positive large) are defined for the inputs and outputs. The universe of discourse taken for the inputs is [-10 10] and that taken for outputs is [-1 1]. The trapazoidal membership functions used for inputs and outputs are shown in Fig. 7 and 8. The 7x7= 49 rules framed with these linguistic variables for fuzzy controller are enlisted in Table 3.

The output responses of this controller are depicted in Fig. 9 and 10.

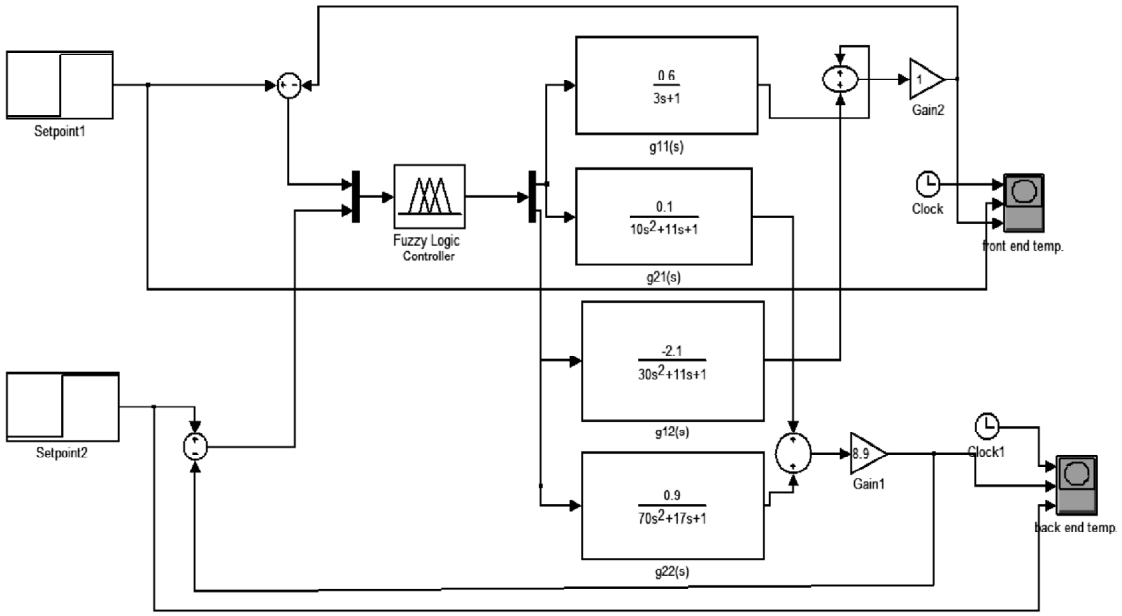

Figure 6: Simulink model of Fuzzy controller

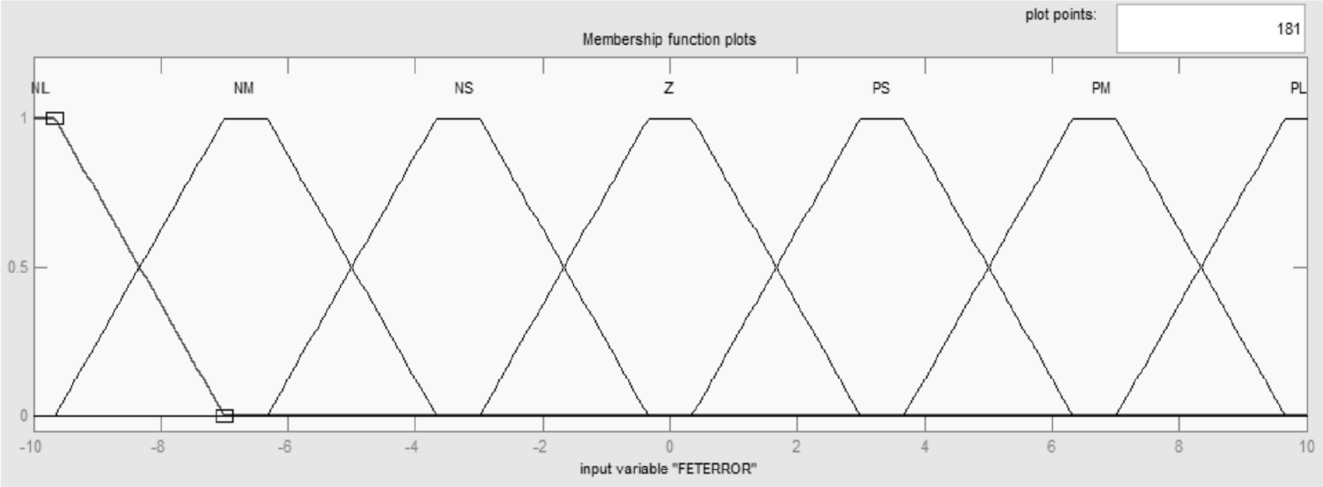

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Figure 7: Membership functions for inputs FET ERROR and BET ERROR

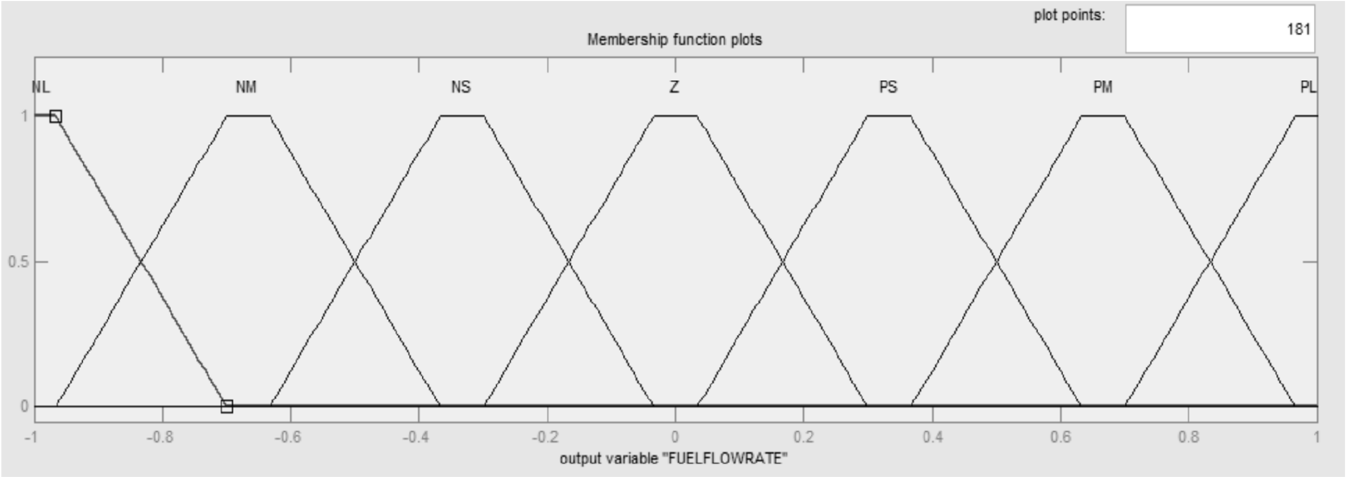

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Figure 8: Membership functions for outputs FUEL FLOW RATE and ID OPENING

Table 3
7x7 rule matrix

RULE NO.	*INPUTS*		*OUTPUTS*	
	FET ERROR	*BET ERROR*	*FUELFLOW RATE*	*ID OPENING*
1	NL	NL	NL	NL
2	NL	NM	NM	NL
3	NL	NS	NS	NL
4	NL	Z	Z	NL
5	NL	PS	PS	NL
6	NL	PM	PM	NL
7	NL	PL	PL	NL
8	NM	NL	NL	NM
9	NM	NM	NM	NM
10	NM	NS	NS	NM
11	NM	Z	Z	NM
12	NM	PS	PS	NM
13	NM	PM	PM	NM
14	NM	PL	PL	NM
15	NS	NL	NL	NS
16	NS	NM	NM	NS
17	NS	NS	NS	NS
18	NS	Z	Z	NS
19	NS	PS	PS	NS
20	NS	PM	PM	NS
21	NS	PL	PL	NS
22	Z	NL	NL	Z
23	Z	NM	NM	Z
24	Z	NS	NS	Z
25	Z	Z	Z	Z
26	Z	PS	PS	Z
27	Z	PM	PM	Z
28	Z	PL	PL	Z
29	PS	NL	NL	PS
30	PS	NM	NM	PS
31	PS	NS	NS	PS
32	PS	Z	Z	PS
33	PS	PS	PS	PS
34	PS	PM	PM	PS
35	PS	PL	PL	PS
36	PM	NL	NL	PM
37	PM	NM	NM	PM
38	PM	NS	NS	PM
39	PM	Z	Z	PM
40	PM	PS	PS	PM
41	PM	PM	PM	PM
42	PM	PL	PL	PM
43	PL	NL	NL	PL
44	PL	NM	NM	PL
45	PL	NS	NS	PL
46	PL	Z	Z	PL
47	PL	PS	PS	PL
48	PL	PM	PM	PL
49	PL	PL	PL	PL

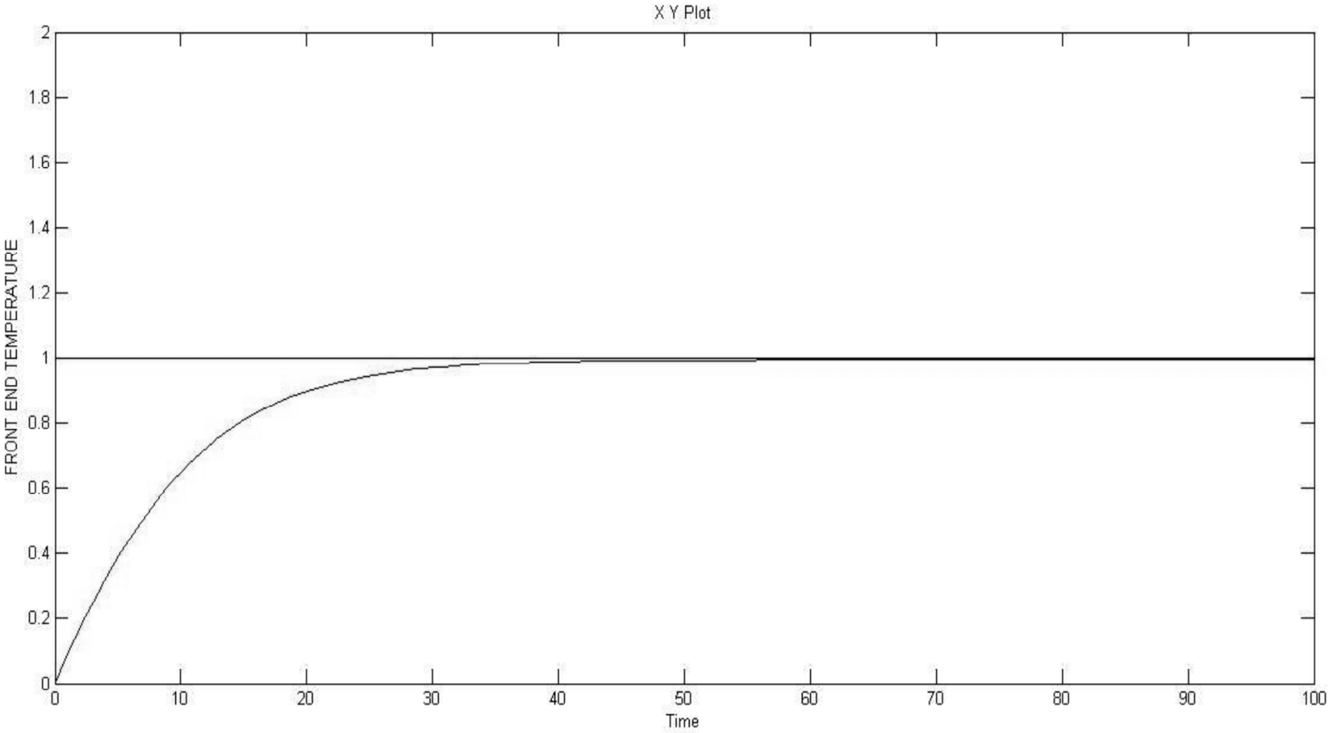

Figure 9: Front end temperature response of Fuzzy controller

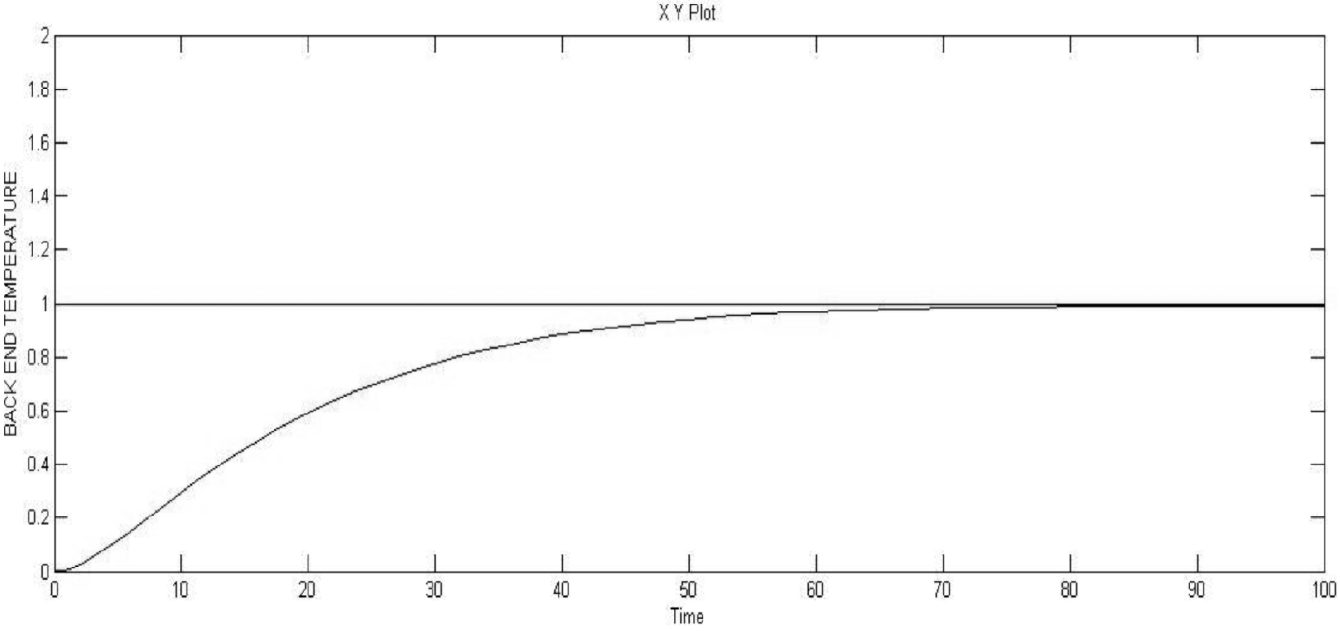

Figure 10: Back end temperature response of Fuzzy controller

The comparision of responses of PI controller and fuzzy controller is showing that the performance of fuzzy controller is much better with no overshoot and smaller settling time.

4. DECOUPLER DESIGN

The MIMO systems have severe loop interactions which degrades the set point tracking performance of the control system. In order to avoid loop interactions decoupling of the system is done. To check the possibility of decoupling usually condition number investigation is done by singular value analysis [13]. It is a matrix technique that determines if a system is able to be decoupled [39]. First of all the eigen values λ_1 and λ_2 of matrix (K^TK) are determined .Then the singular values s_1 and s_2 are determined by taking square root of λ_1 and λ_2 respectively.

Now, let's introduce a parameter called condition number (CN) which is defined as,

$$CN = \frac{s_1}{s_2};\ if \quad s_1 \geq s_2 \tag{10}$$

$$Or\ \ CN = \frac{s_2}{s_1};\ if \quad s_2 \geq s_1 \tag{11}$$

As a thumb rule, if CN is greater than 50 then it is impossible to decouple the given MIMO system.

The eigen values of the matrix K^TK for the considered lime kiln process comes out to be $\lambda_1 = 0.1025$ and $\lambda_2 = 5.4875$.The corresponding singular values are s_1=0.3202 and s_2=2.3425.

Hence the condition number (CN) using relation (11) is,

CN=2.3425/0.3202=7.3 showing that decoupling is possible.

Now let G(s) be the transfer matrix of a 2x2 MIMO system.

$$[G(s)] = \begin{bmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{bmatrix} \tag{12}$$

Then, the interaction compensator matrix for achieving decoupling is given below [16],

$$[G_1(s)] = \begin{bmatrix} 1 & g_{I1}(s) \\ g_{11}(s) & 1 \end{bmatrix} \tag{13}$$

Where,

$$g_{I1}(s) = \frac{-g_{12}(s)}{g_{11}(s)} \tag{14}$$

$$g_{I2}(s) = \frac{-g_{21}(s)}{g_{22}(s)} \tag{15}$$

Here $g_{I1}(s)$ and $g_{I2}(s)$ are the gains of the interaction compensators for loop 1 and loop 2 respectively.

Now, the modified simulink model incorporating the two interaction compensators (decouplers) using relations (14) and (15) is shown in the figure 11.

The following relations hold good for the model in figure 11.

$$\begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} = [G_I(s)] \begin{bmatrix} v_1(s) \\ v_2(s) \end{bmatrix} \tag{16}$$

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = [G(s)] \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} \tag{17}$$

Here $v_1(s)$ and $v_2(s)$ are the outputs of the two PI controllers of figure 11.

Combining relations (16) and (17) we get,

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = [G(s)][G_I(s)] \begin{bmatrix} v_1(s) \\ v_2(s) \end{bmatrix} \tag{18}$$

Which gives the following results,

$$y_1(s) = \left[g_{11}(s) - \frac{g_{12}(s)g_{21}(s)}{g_{22}(s)} \right] v_1(s) \tag{19}$$

$$y_2(s) = \left[g_{22}(s) - \frac{g_{12}(s)g_{21}(s)}{g_{11}(s)} \right] v_2(s) \tag{20}$$

Thus we get two independent decoupled SISO systems v_1-y_1 (decoupled SISO1) and v_2-y_2(decoupled SISO2) with gains $G_1(s)$ and $G_2(s)$.The expressions for $G_1(s)$ and $G_2(s)$ determined using relations (19) and (20) are given in relations (21) and (22).

$$G_1(s) = \frac{162\,s^4 + 281.7\,s^3 + 112.3\,s^2 + 16.08 + 0.75}{810\,s^5 + 1458\,s^4 + 830.7s^3 + 204.3s^2 + 22.5s + 0.9} \tag{21}$$

$$G_2(s) = \frac{162\,s^4 + 281.7\,s^3 + 112.3\,s^2 + 16.08\,s + 0.75}{12600\,s^6 + 21540\,s^5 + 11430\,s^4 + 2830s^3 + 363s^2 + 23.4s + 0.6} \tag{22}$$

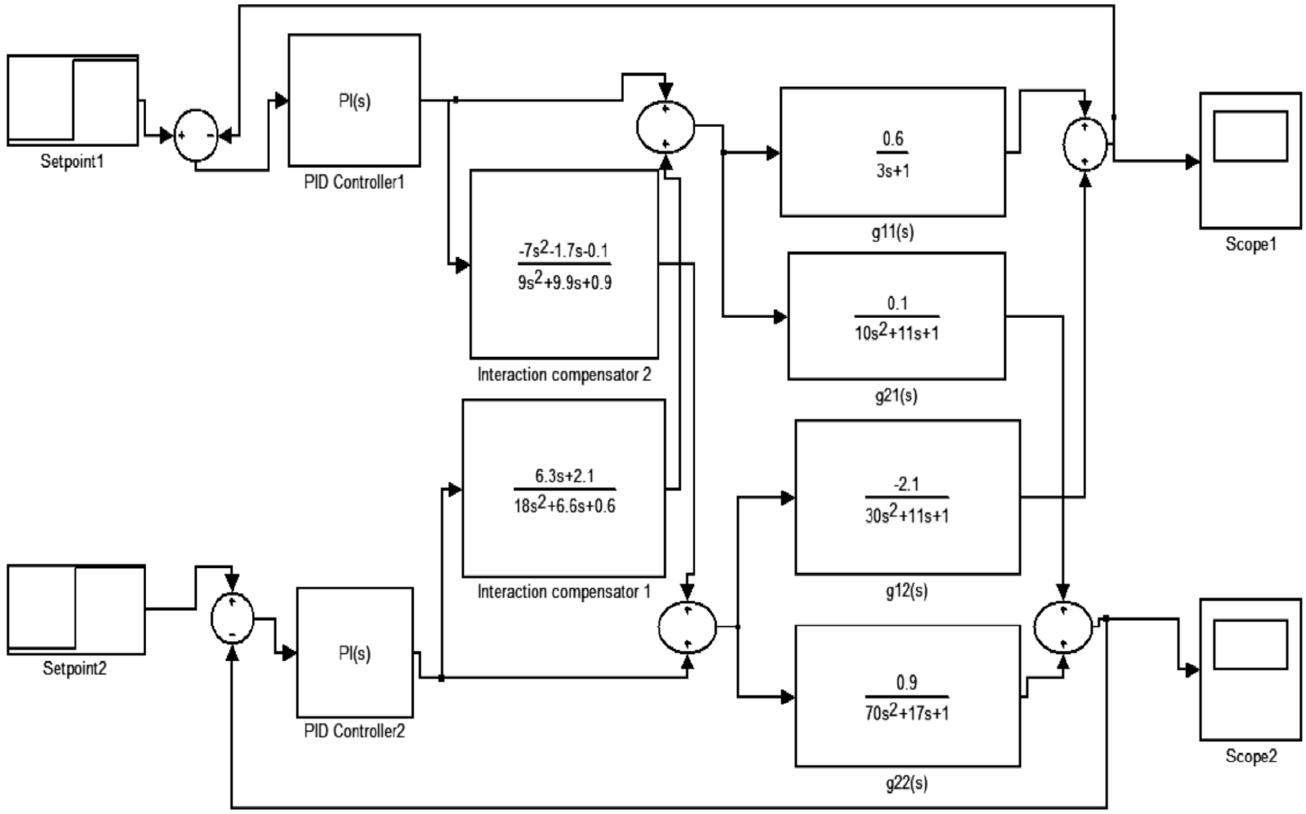

Figure 11: PI controller with decouplers

The corresponding setpoint tracking responses with tuned values K_p=0.8143 and K_i=0.6532 for controller1 and K_p=1.6527 and K_i=0.0859 are depicted in Fig. 12 and 13.The characterstics of these responses are specified in Table 4 and 5.These responses reveal that the set point tracking is excellent after decoupling and it is much better than the composite system.

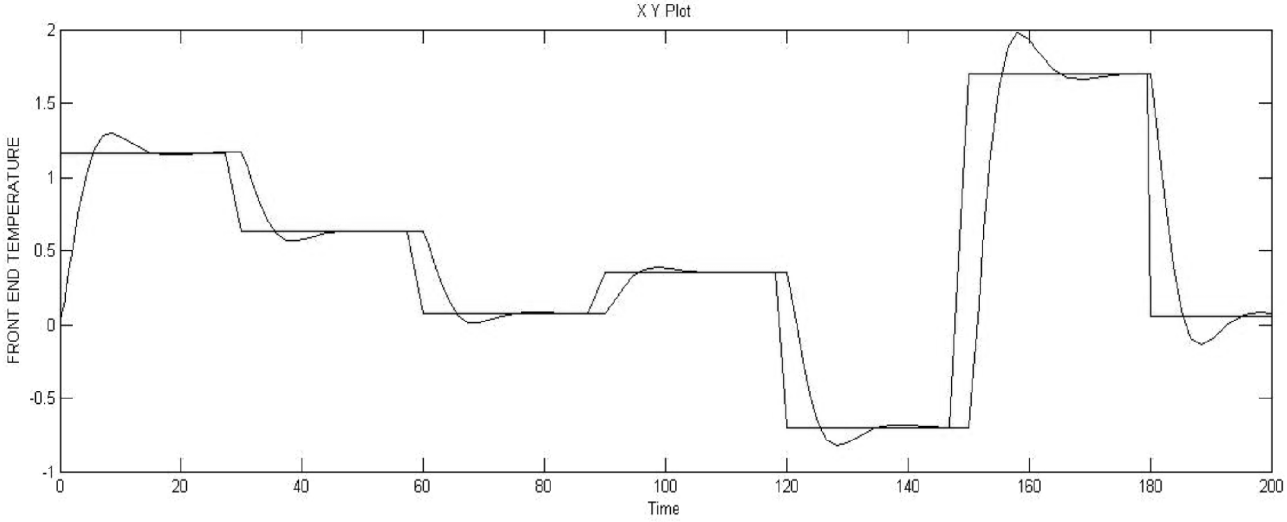

Figure 12: Setpoint tracking response of front end temperature with decouplers

Table 4
Closed loop step response characterstics of decoupled SISO 1 system

Parameter	*Value*
Rise time(sec)	3.97
Setteling time(sec)	13.6
Overshoot (%)	12
Peak amplitude	1.12

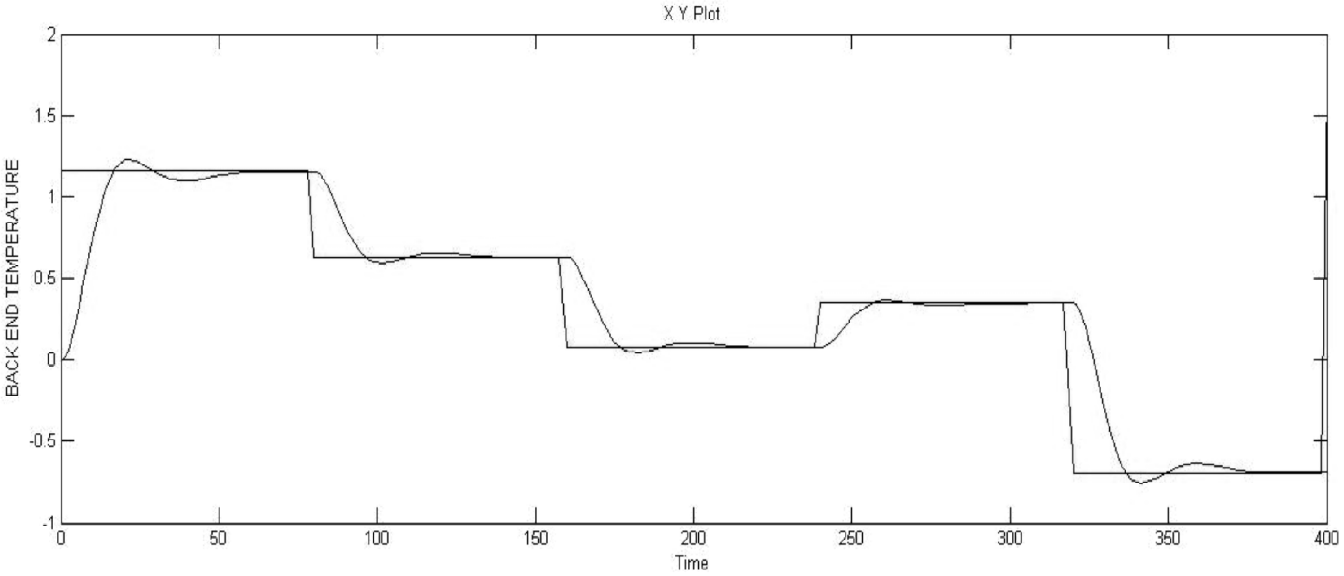

Figure 13: Setpoint tracking response of back end temperature with decouplers

Table 5
Closed loop step response characterstics of decoupled SISO 2 system

Overshoot (%)	*12*
Parameter	Value
Rise time(sec)	10.9
Setteling time(sec)	52.8
Overshoot (%)	5.93
Peak amplitude	1.06

6. CONCLUSION

In the present work the multivariable analysis of a lime kiln plant has been done by determining RGA which suggested the suitable loop pairing for designing controller.The calculated value of Niederlinski index indicated that this system has good closed loop stability.

The multiloop controller has been designed using PI and fuzzy logic procedure and an acceceptable setpoint tracking performance was observed.After decoupling, the controller performance has been observed to be better than the multiloop controller for the composite system.

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