Temperature Controller for Continuous Stirred Tank Reactor using Adaptive PSO Based PID Controller

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Abstract— The objective of the project is to control the reactant temperature of a Continuous Stirred Tank Reactor (CSTR) by manipulating the coolant temperature. The plant is modeled mathematically for the normal operating condition of CSTR. Then the transfer function model is obtained from the process. The various different kinds of controller is designed and implemented to control the temperature of the CSTR system, such as conventional method (Trial and Error method), Ziegler- Nichols method, Fuzzy logic method, PSO tuned PID controller method and Adaptive PSO tuned PID controller method. The servo response is obtained for the different operating condition of temperatures. From the servo response, Adaptive PSO algorithm based PID tuning method has given better setpoint tracking capability than the Ziegler-Nichols method, Conventional PID method, Fuzzy logic method, Particle swarm optimization (PSO) algorithm based PID tuning method. . In particular, our experience supports the conjecture that Adaptive PSO algorithm based optimal tuning of PID controller method offer advantages over all other controller method
.

Index Terms—**Conventional PID Controller, Z-N PID Controller, Fuzzy PID Controller, APSO and CSTR.**

I. INTRODUCTION

In chemical industries one of the complex dynamics system is Continuous Stirred Tank Reactor (CSTR). The temperature controlling of the complex CSTR is very difficult by using linear controller. In a Continuous Stirred Tank Reactor (CSTR), reactants and products are continuously added and continuous collected in the outlet. An electrical motor is used to mixer the content and it is required to achieve uniform composition and temperature of the mixer. The continuous stirred-tank reactor (CSTR), also known as vat reactor, it is a general reactor type in chemical industries. Chemical kinetics and reactor design are at the heart of producing almost all industrial chemicals. The reaction occurred in a reactor is exothermic or endothermic.
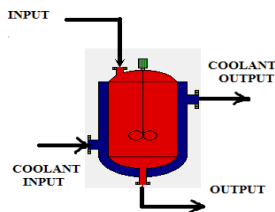

Fig. 1. Continuous Stirred Tank Reactor

The reactor is having a jacket or coil in order to maintain the reaction temperature in the reactor. While chemical reaction takes place inside the reactor, there is a chance to producing heat or chance to getting cold. If endothermic reaction takes place in the CSTR, a process or reaction in which the system absorbs energy from its surroundings in the form of heat, so

the flow of heating medium is passing through jacket or coil for maintain the reaction temperature in the CSTR. A reactor operates at a constant temperature, then that is called as the isothermal reactor. The temperature of the reactions varies with time and we need to control temperature of the CSTR reactor in order to produce good quality product because of endothermic and exothermic reactions. In chemical industries the temperature control is very important because it will completely affect the product.

II. CALCULATING TRANSFER FUNCTION MODEL FOR DIFFERENT OPERATING CONDITIONS OF CSTR

Mass and energy balance equation of CSTR is following

$$\frac{dC_A(t)}{dt} = \frac{q(t)}{V}(C_{AO}(t) - C_A(t)) - K_O e^{\left(\frac{-E}{RT(t)}\right)} C_A(t) \tag{2.1}$$

$$\frac{dT(t)}{dt} = \frac{q(t)}{V}(T_0(t) - T(t)) - ((-\Delta H)K_0 C_A(t)e^{\left(\frac{-E}{RT(t)}\right)}) + \frac{\rho_c c_{pc}}{\rho_c c_p V} q_c(t)\left(1 - e^{\frac{-hA}{q_c(t)\rho t_p}}\right)(T_{co}(t) - T(t)) \tag{2.2}$$

Where,

$C_A(t)$ - Concentration in mol/lit

$T(t)$ - Reactor Temperature in Kelvin

A. *State Space Model of CSTR*

The general state space model is following,

$\dot{x} = Ax + Bu$

$y = Cx + D$, State variables are, $\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} C_A \\ T \end{bmatrix}$

Where,

$u = q_c(t)$ Coolant flow rate L/min.

$$\dot{X} = \begin{bmatrix} \dfrac{\partial f_1}{\partial x_1} & \dfrac{\partial f_1}{\partial x_2} \\ \dfrac{\partial f_2}{\partial x_1} & \dfrac{\partial f_2}{\partial x_2} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \begin{bmatrix} \partial f_1/\partial u \\ \partial f_2/\partial u \end{bmatrix} [u] \qquad (2.3)$$

TABLE I. NORMAL OPERATING CONDITION OF CSTR

Sl. No.	Process variable	Normal operating condition
1.	Concentration(CA)	0.0885 mol/lit
2.	Reactor Temperature(T)	441.1475 K
3.	Volumetric Flow Rate(q)	100 L/min
4.	Reactor Volume(V)	100l
5.	Feed Concentration(CAf)	1 mol/Lit
6.	Feed Temperature(Tf)	350 K
7.	Coolant Temperature(Tcf)	350 K
8.	Coolant Flow Rate(qc)	97 L/min
9.	Heat of Reaction(ΔH)	2e5 cal/mol
10.	Reaction Rate Constant(Ko)	7.2e10 /min
11.	Activation Energy term(E/R)	9980 K
12.	Heat Transfer term(hA)	7e5 cal/(min*K)

Finding Transfer function

For q_c = 97 L/min.
C_A = 0.08235mol/Lit.
T = 443.4566 K

The system transfer function,

$$G(s) = \frac{1.503s + 18.26}{s^2 + 21.53s + 9.403} \qquad (2.4)$$

TABLE II. TRANSFER FUNCTION FOR DIFFERENT OPERATING POINTS

Sl. No.	Qc (lit/m)	CA (mol/lit)	Temper ature (K)	Transfer function
1	97	0.0795	443.456	$\text{System1} = \dfrac{1.414s + 18.51}{s^2 + 22.87s + 9.497}$
2	100	0.0885	441.147	$\text{System2} = \dfrac{1.492s + 17.57}{s^2 + 21.55s + 9.782}$
3	103	0.0989	438.776	$\text{System3} = \dfrac{1.582s + 16.71}{s^2 + 20.34s + 10.22}$
4	106	0.1110	436.309	$\text{System4} = \dfrac{1.681s + 15.87}{s^2 + 19.2s + 10.36}$
5	109	0.1254	433.692	$\text{System5} = \dfrac{1.788s + 15}{s^2 + 18.11s + 10.62}$

III. DESIGN OF CONTROLLERS

A. Design of Conventional Controller

Conventional controller is controller where the controller parameters like kp, ki, kd are all tuned by guess and check method i.e. called "Trial and error "method. Because of random choices trial and error method will take large time to tuning the controller parameters of the controller. The following tuning rule present in book titled "The Michigan chemical process dynamics and controls open text book" by prof. Peter Woolf, 2007.

TABLE III. TRIAL AND ERROR METHOD TUNING RULE

Sl. No.	Gains	Temperature process
1.	Kp	2-10
2.	ki	2-10
3.	kd	0-5

For the temperature process the controller parameters are taken from the Table III. Let the controller parameters are,

$$K_P = 8; \ K_i = 3; \ k_d = 1$$

$$G(s) = \frac{1.492s + 17.57}{s^2 + 21.55s + 9.782} \qquad (3.1)$$

B. Ziegler-Nichols PID-Controller

A proportional-integral-derivative controller (PID controller) is a popular controller, which is widely used in all industrial because of its advantages in control systems. PID controller- proportional-integral-derivative controller.
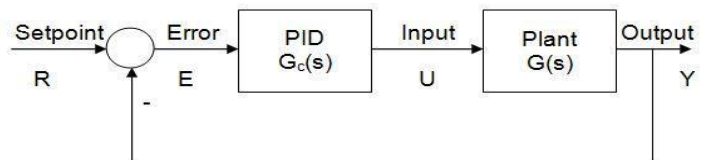
Fig. 2. Block diagram of PID controller with G(S) Plant

Thus the above diagram shows the general Ziegler-Nichols PID controller with plant G(s) which is shown by figure.

$$u(t) = K_P e(t) + K_i \int_0^t e(t)dt + K_d \frac{d}{dt} e(t) \qquad (3.2)$$

Where,

K_p = Proportional gain
T_i = $1/K_i$ = Integral gain
T_d = $1/K_d$ = Derivative gain
E = error = Set point-process variable

It was developed by John G. Ziegler and Nathaniel B. Nichols. Ziegler-Nichols tuning rule was the first such effort to provide a practical approach to tune a PID controller.

TABLE IV. ZIEGLER NICHOLS TUNING RULE

Sl. No.	Controller	Kc	Ti	Td
1.	P	Ku/2	-	-
2.	PI	Ku/2.2	Pu/1.2	-
3.	PID	Ku/1.7	Pu/2	Pu/8

Ziegler-Nichols tuning rule gives sometime better results but not suitable for all process. Because of the improper tuned controller parameters. This is one of the major disadvantage in Ziegler-Nichols controller.

TABLE V. CONTROLLER PARAMETERS FOR DIFFERENT OPERATING TEMPERATURES

Sl.No.	Different temperature condition	Controller Types	Controller types
1.	T=443.4566 Ku=1.3153 Pu=6.2724	P	Kc=0.657
		PI	Kc=0.597 Ti=5.229
		PID	Kc=0.773 Ti=3.137 TD=0.784
2.	T=441.1475 Ku=1.3393 Pu=6.1683	P	Kc=0.669
		PI	Kc=0.608 Ti=5.142
		PID	Kc=0.787 Ti=3.085 TD=0.771
3.	T=438.776 Ku=1.3714 Pu=6.0460	P	Kc=0.68
		PI	Kc=0.62 Ti=5.04
		PID	Kc=0.80 Ti=3.02 TD=0.7
4.	T=436.3091 Ku=1.3941 Pu= 5.9537	P	Kc=0.69
		PI	Kc=0.63 Ti=4.96
		PID	Kc=0.82 Ti=2.97 TD=0.7
5.	T=433.692 Ku=1.4312 Pu=5.8413	P	Kc=0.715
		PI	Kc=0.650 Ti=4.870
		PID	Kc=0.841 Ti=2.922 TD=0.730

TABLE VI. TIME DOMAIN PARAMETERS FOR DIFFERENT CONTROLLERS

Sl. No	Time domain characteristics	Trial and Error method	Z-N method	Fuzzy logic method	PSO-PID method	APSO-PID method
1	Settling time (sec)	4.5	9.2	8.52	4.7	**4.12**
2	Rise time (sec)	1.3	2.64	2.23	1.98	**1.87**
3	Overshoot (%)	0	23.6	22.42	0	**0**

C. Fuzzy PID-Controller

Fuzzy logic control is an efficient control for problems which are nonlinear and has scarce knowledge regarding them. Fuzzy inference system is a popular computing technique. Fuzzy is basically rule base methodology for computing different tasks. Here fuzzy is used to compute the gain values of the PID controller. The input to the fuzzy tuned controller is the error and change in error and the outputs are the PID gain values. The membership function used is a triangular membership function and defuzzification method used is centroid.

Advantages of Fuzzy Logic Controller over Ziegler Nichols Controller,

- Fuzzy PID Controller used for Non-Linear process.
- Here dynamic behaviour of the process can be captured.
- Process output meet the desired set point quickly.

D. Design Procedure of Fuzzy Logic PID Controller

- Build and tune a conventional PID controller first.

- Replace it with an equivalent linear fuzzy controller.
- Make the fuzzy controller nonlinear.
- Fine-tune the fuzzy controller.

TABLE VII. FUZZY LOGIC CONTROLLER TUNING RULE

Sl.No	Controller	Kp	1/Ti	Td
1.	Fuzzy P	GE*GU	_	_
2.	Fuzzy PI	GCE*GU	_	GCE/GE
3.	Fuzzy PID	GE*GU	GIE/GE	GCE/GE

The controller parameters are tuned by fuzzy logic technique as in ([1],[3],[8]).

TABLE VIII. FUZZY LOGIC RULES

E	EC K_P K_I K_D	NB	NM	NS	ZO	PS	PM	PB
NB		PB	PB	PM	PM	PS	PS	ZO
		NB	NB	NB	NM	NM	ZO	ZO
		PS	PS	ZO	ZO	ZO	PB	PB
NM		PB	PB	PM	PM	PS	ZO	ZO
		NB	NB	NM	NM	NS	ZO	ZO
		NS	NS	NS	NS	ZO	NS	NM
NS		PM	PM	PM	PS	ZO	NS	NM
		NM	NM	NS	NS	ZO	PS	PS
		NB	NB	NM	NS	ZO	PS	PM
ZO		PM	PS	PS	ZO	NS	NM	NM
		NM	NS	NS	ZO	PS	PS	PM
		NB	NM	NM	NS	ZO	PS	PM
PS		PS	PS	ZO	NS	NS	NM	NM
		NS	NS	ZO	PS	PS	PM	PM
		NB	NM	NS	NS	ZO	PS	PS
PM		ZO	ZO	NS	NM	NM	NM	NB
		ZO	ZO	PS	PM	PM	PB	PB
		NM	NS	NS	NS	ZO	PS	PS
PB		ZO	NS	NS	NM	NM	NB	NB
		ZO	ZO	PS	PM	PB	PB	PB
		PS	ZO	ZO	ZO	ZO	PB	PB

IV. SIMULATION AND RESULTS

By using Matlab the system was modelled and simulated. The simulated results of the system control with closed loop method and Conventional Controller and Z-N PID-Controller and Fuzzy PID-Controller were analysed.
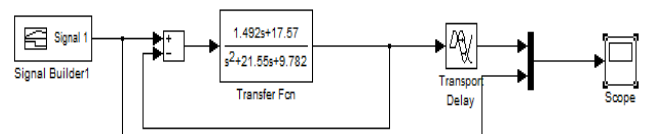Figure 3, shows the Simulink block diagram of the closed loop systems.

Fig. 3. Simulink Block Diagram for Closed loop systems

Figure 4, shows the Simulink block diagram of Ziegler-Nichols PID-Controller.
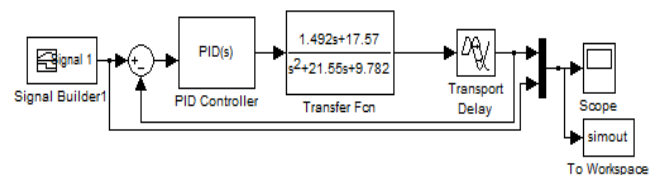

Fig. 4. Simulink Block Diagram for PID-Controller

Figure 5, shows the Simulink block diagram of fuzzy PID-Controller
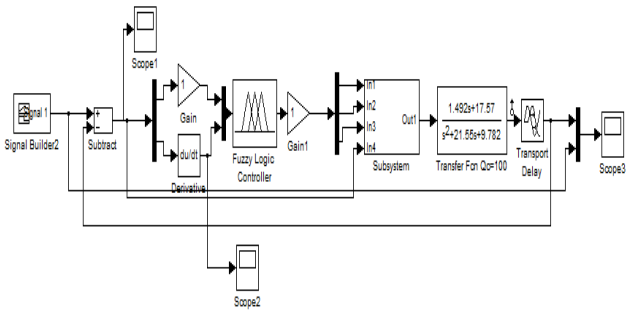
Fig. 5. Simulink Block Diagram for Fuzzy PID-Controller

Figure 6, shows the servo response of closed loop system, the process output doesn't meet the desired set point.
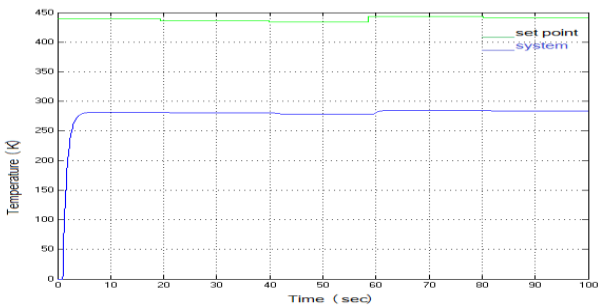

Fig. 6. Servo Response of Closed loop Systems

Figure 7, shows the servo response of Trial and Error Method, the process output meet the desired set point quickly. The Controller parameters are Kp=8; Ki=3; kd=1 as in TABLE III. For simulation purpose equation (3.1) was used.
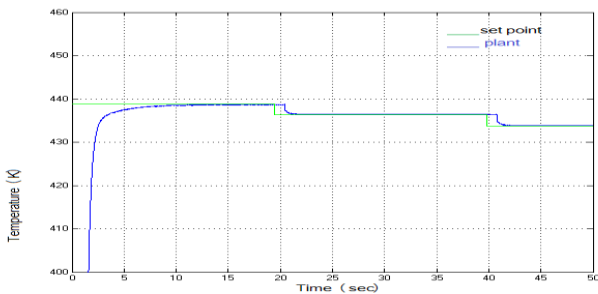

Fig. 7. Servo Response of Trial and Error Method

Figure 8, shows the servo response of Ziegler-Nichols PID-Controller and Fuzzy PID-Controller, In the Fuzzy PID-Controller, The process output meet the desired set point quickly with less oscillation than the Ziegler-Nichols PID-Controller. The Controller parameters are Kp=0.7878; Ki=3.0857; Kd=0.7714 as in TABLE V. For simulation purpose equation (3.1) was used.
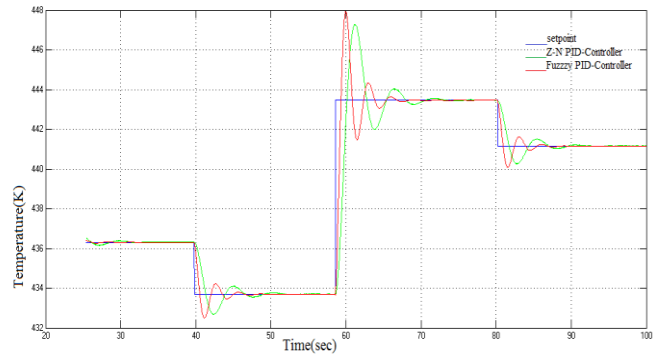

Fig. 8. Servo Response Comparison of Ziegler-Nichols PID-Controller and Fuzzy PID-Controller
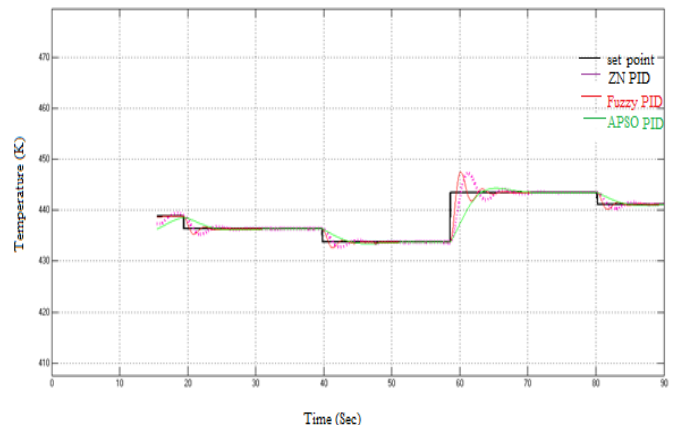

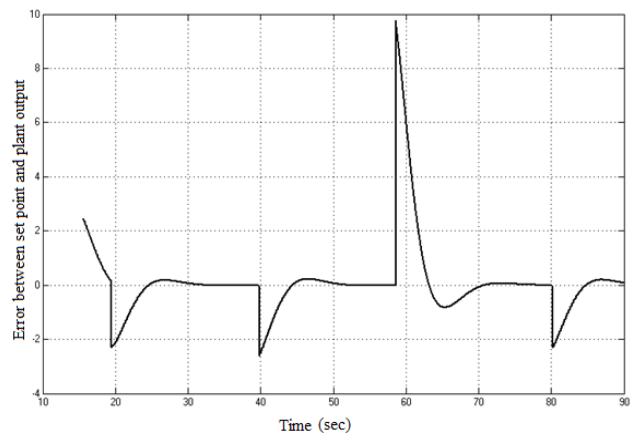Fig. 10. Servo Response for APSO PID-Controller
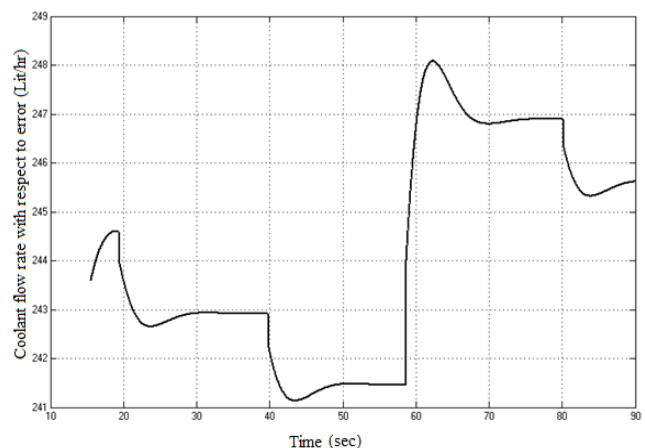

Fig. 11. Error Response for APSO PID-Controller

Fig. 12. Coolant Flow Rate with respect to Error for APSO PID-Controller

The following table shows the analysis between the error and coolant flow rate for APSO-PID controller method.

TABLE IX ERROR VS. COOLANT FLOW RATE (LIT/HR) FOR APSO PID-CONTROLLER

Sl. No	Error	Coolant flow rate (lit/hr)
1	-2	243.5
2	0	243
3	-2	242
4	0	241.5
5	10	248
6	0	247
7	-2	246.3
8	0	245.5

TABLE X PID PARAMETERS VALUES FOR DIFFERENT CONTROLLERS

Sl. No	PID parameters	Trial and Error method	Z-N method	Fuzzy logic method	PSO-PID	APSO-PID method
1	K_p	8	0.7878	0-1.5	0.1296	0.1196
2	K_i	3	3.05857	0-1.5	0.1367	0.2264
3	K_d	1	0.7714	0-0.5	0.0956	0.0811

V. CONCLUSION

The mathematical modelling of the process is done for all five operating conditions. The ZN-PID controller, Fuzzy based PID and PSO-PID controller are able to maintain the set point at the desired value. However, the performances of APSO based PID controller at all operating points are found to be better than ZN-PID ,Fuzzy based PID and PSO-PID controller, as there is less overshoot and settles to the set point faster. The APSO based PID controller provides a better performance compared to ZN-PID controller. The PID controller gains were tuned and the proposed methodology is shown better performance when compared with the traditional methodology, fuzzy logic controller and standard PSO tuned PID controller for the CSTR process.

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