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Robust PID Tuning of Heat Exchanger System Using Swarm Optimization Method

Sapna Gupta, Rajeev Gupta

***Abstract:** Though there are numerous tuning methods available for PID controller, most of the time the controller is tuned using trial and error method. The trial and error based tuning of PID controller leads to deterioration in control performance. One of the solution of trial and error based tuning is to either find the optimal tuning parameters using any of the tuning rule or find the optimal tuning parameters using any of the optimization algorithms. There are several evolutionary and swarm intelligence based optimization techniques available in literature. This paper finds the optimal tuning parameter using particle swarm optimization (PSO) and implements the results in a heat exchanger control problem to validate the results.*

***Index Terms:** PID controller, Particle swam optimization, Swarm Optimization, Tuning*

I. INTRODUCTION

PID controller is one of the most widely used classical controllers in regulatory and servo control problems. It is widely used in oil refineries, chemical plants, and paper and pulp industry. There are thousands of PID controllers in hundreds of control loop in industry. PID controller can be used either as a standalone device or it can be used in distributed control.

The wide acceptance is because of its simple architecture and simpler operation. PID controller has three components such as proportional gain, integral gain and derivative gain. Proportional gain reduces the overshoot, integral gain reduces the steady state error and derivative gain makes the controller act faster.

There are various tuning algorithms for PID controller [1,2]. The most widely used tuning method is Zeigler-Nichols tuning method. In Zeigler-Nichols tuning method, ultimate gain and period is calculated and from the above information, PID parameters are calculated. But the calculated gains of PID controller may or mayn't be optimal for practical purposes. Therefore, researchers have used evolutionary algorithms [3] and swarm optimization based techniques [4-8] for PID tuning. Out of many swarm optimization algorithms particle swarm optimization (PSO) is one of the emerging algorithms because of its faster convergence and optimal results.

This paper implements PSO based PID tuning algorithm to calculate the PID parameters for feedback control of a heat exchanger system.

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* Correspondence Author
Sapna Gupta*, Department of Electronics Engineering, University College of Engineering, Rajasthan Technical University, Rajasthan, India.
Rajeev Gupta, Department of Electronics Engineering, University College of Engineering, Rajasthan Technical University, Rajasthan, India.

II. HEAT EXCHANGER

Heat exchanger is one of the important units of chemical plants and it is used for high pressure applications. Shell and tube heat exchanger is one of the widely used heat exchanger. This kind of heat exchanger consists of shell with bundle of tubes. One fluid run through the shell and other fluid runs through the tube to transfer heat between two fluids. Figure 1 shows the basic block diagram of shell and tube heat exchanger. In the heat exchanger, temperature T_o should be controlled.

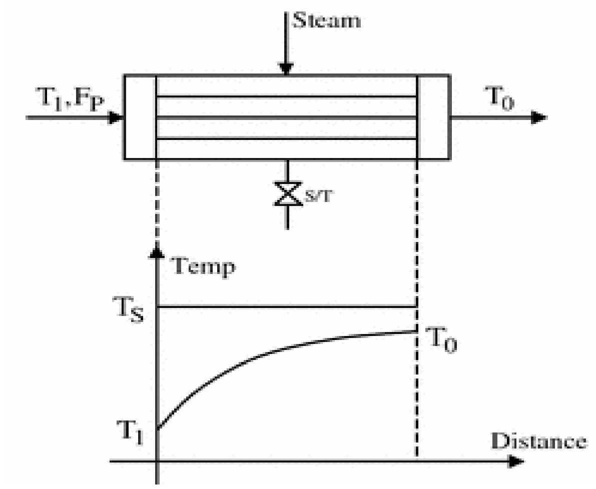

Fig. 1. **Schematic of shell and tube heat exchanger system**

A. Linearized Modeling of Shell and Tube Heat Exchanger

To control the outlet temperature T_o, different controllers can be used. This paper uses PID controller for the purpose. The first task of controller design is to develop a mathematical model of the system. This section develops a linearized transfer function model of the shell and tube heat exchanger system. To develop the experimental model, the experimental data is considered which is reported in [9,10].

From the experimental data, following model is developed.

Transfer function of process is considered as

$$G_p(s) = \frac{Y(s)}{T(s)} = \frac{5e^{-s}}{90s^2 + 33s + 1} \qquad (1)$$

Transfer function of inlet flow disturbance is considered as,

$$G_d(s) = \frac{Y(s)}{D(s)} = \frac{1}{30s + 1} \qquad (2)$$

Transfer function of sensor is considered as

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$$G_h(s) = \frac{Y(s)}{B(s)} = \frac{0.16}{10s+1} \qquad (3)$$

Transfer function of PID controller is represented as

$$G_c(s) = \frac{U(s)}{E(s)} = K_p + K_d s + \frac{K_i}{s} \qquad (4)$$

The complete transfer function can be represented as

$$Y(s) = \frac{G_c(s)G_p(s)}{1+G_c(s)G_p(s)G_h(s)} R(s) + \frac{G_d(s)}{1-G_c(s)G_p(s)G_h(s)} D(s) \qquad (5)$$

The control block diagram of shell and tube heat exchanger is shown in figure 2.

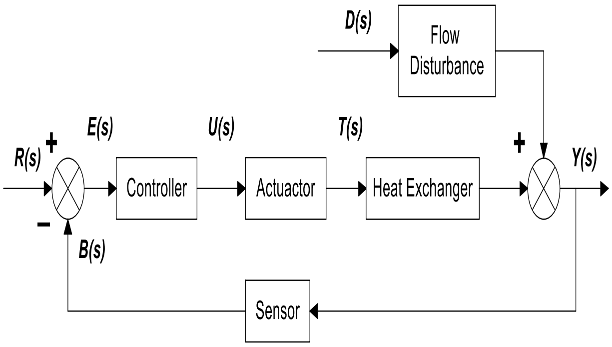

Fig. 2. **PID control of shell and tube heat exchnager system**

III. PARTICLE SWARM OPTIMIZATION

Particle swarm optimization (PSO) is a bio-inspired meta-heuristic technique proposed by James Kennedy and Russell Eberhart in 1995 [11]. PSO performs a population-based search, using particles to represent potential solutions within the search space. Each particle is characterized by its position, velocity, and a record of its past performance. Particles are influenced by their leaders, which are the best performers either from the entire swarm or their neighbourhood. At each flight cycle, the objective function is evaluated for each particle, with respect to its current position, and that information is used to measure the quality of the particle and to determine the leader in the sub-swarms and the entire population. Figure 3 shows the flow chart of PSO. The position of each agent in the swarm population is known by position and velocity. Each agent knows its best value p_{best} and best value so far in group g_{best} among p_{best}.

Each agent modifies its position using the following criteria

i) Current position
ii) Current velocity
iii) Distance between current position and pbest
iv) Distance between current position and g_{best}

The velocity updating is done using the following equations

$$V_i^{k+1} = wV_i^k + C_1 rand\left(p_{best_i} - s_i^k\right) + C_2 rand\left(g_{best_i} - s_i^k\right) \quad (6)$$

$$w = w_{max} - \frac{(w_{max} - w_{min})}{N_{max}} N \qquad (7)$$

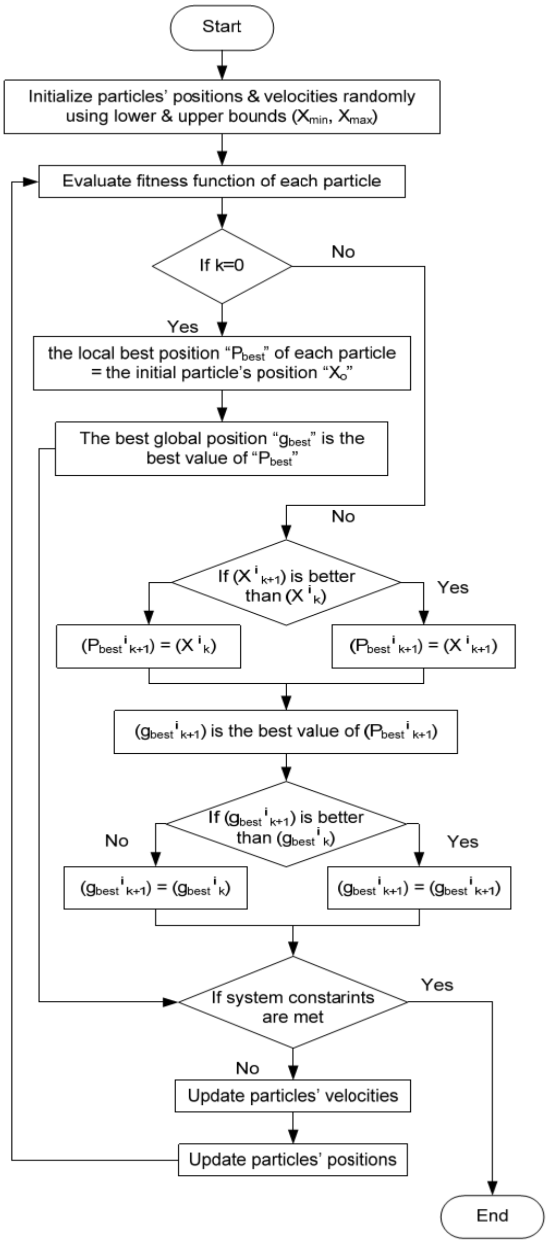

Fig. 3. **Flow chart of PSO**

Here c_1 and c_2 are acceleration constant, N is number of iteration, N_{max} is maximum number of iterations and w is inertia weight factor

B. PID Tuning Using PSO

For optimal tuning of PID controller parameter, PSO is used. The block diagram of PSO tuning of PID controller is shown in figure 4.

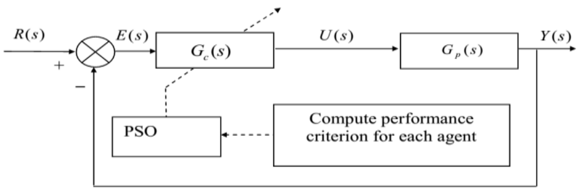

Fig. 4. **PID tuning using PSO: Block diagram**

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In PSO tuning of PID controller, optimal value of [k_p, k_i and k_d] are obtained which exhibits less overshoot, has a moderate level of settling time, low rise time and zero steady state error. The objective function of PSO consists of these terms and PSO algorithm minimizes the objective function.
Objective function of PSO considered in this paper is

$$\min_{(K_p K_i K_d)} W(K) = \left(1-e^{-\beta}\right)\left(M_p + e_{ss}\right) + e^{-\beta}\left(t_s - t_r\right)$$

Subject to,

$$0 \le K_p \le K_{p(\max)}$$

$$0 \le K_i \le K_{i(\max)}$$

$$0 \le K_d \le K_{d(\max)}$$

Here,

β Weighing factor

M_p Peak overshoot

e_{ss} Steady state error

t_s Settling time

t_r Rise time

$K_{p(\max)}, K_{i(\max)}, K_{d(\max)}$ are maximum values of K_p, K_i, K_d respectively

The complete flow chart of PSO tuning of PID controller is shown in figure 5. In this paper, following parameters of PSO are considered. β = 0.5, c_1 = 2 and c_2 = 2

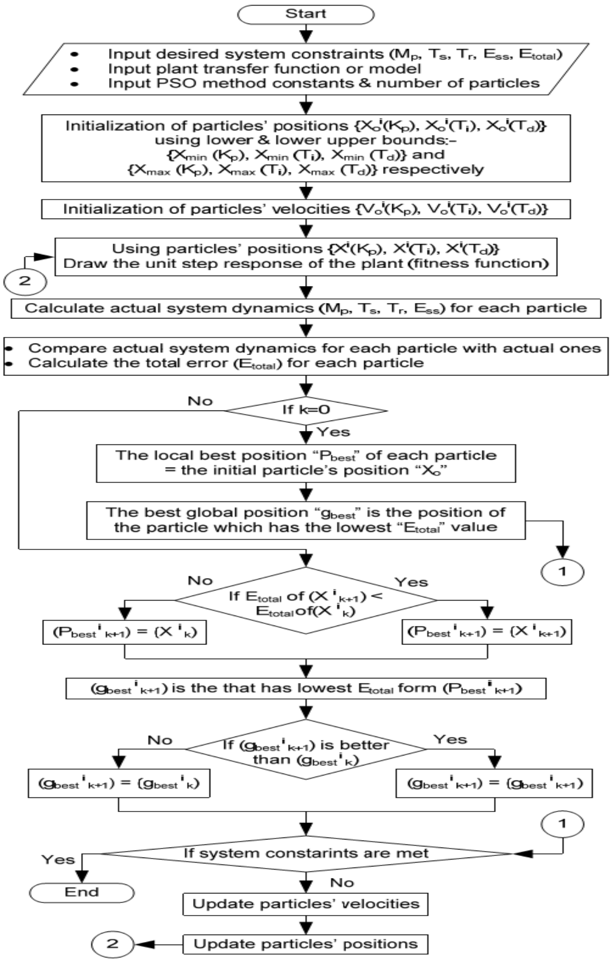

Fig. 5. **PID tuning using PSO: Algorithm**

IV. RESULTS

This section discusses the results obtained to meet the control objectives. First of all the stability of heat exchanger system is checked using Bode plot which is shown in figure 6.

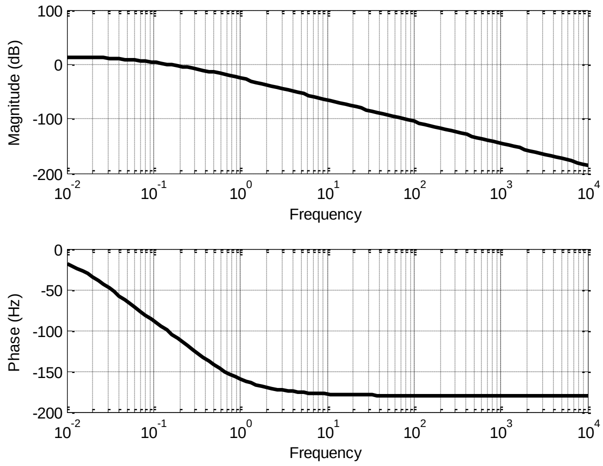

Fig. 6. **Stability analysis of system**

From the bode plot it is observed that GM is 36.4 dB and PM is 77.8°,So the heat exchanger is stable.
A controller has two main objectives, i.e set point tracking and disturbance rejection. Unit step function is provided to test the above mentioned objectives. Simulation results in figure 7 shows the set point tracking feature of the controller. In set point tracking objective, the controller exhibits a peak overshoot of 17% and zero steady state error.

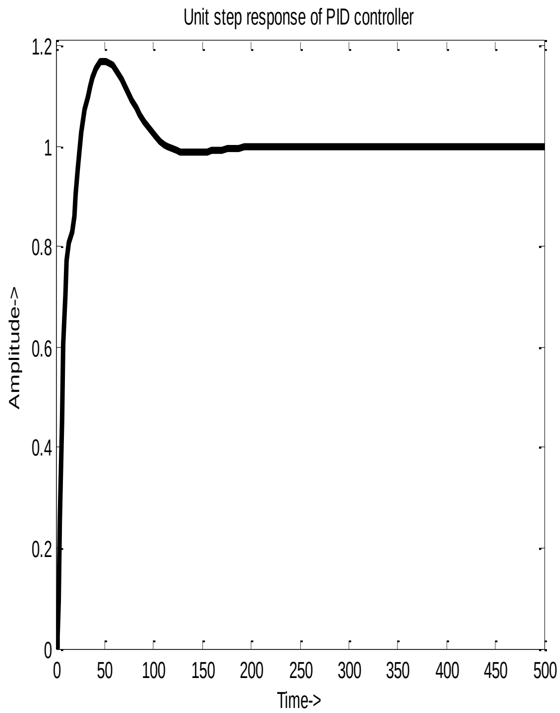

Fig. 7. **Unit step response of system using PID controller tuned using Z-N Method exhibiting set point tracking feature**

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To test the load disturbance objective, two kinds of load are used i.e step disturbance and pulse disturbance. The unit step response of controller compensating the step load disturbance at 250 sec is shown in figure 8. In this case, the controller has slightly high peak overshoot of 29.56%.

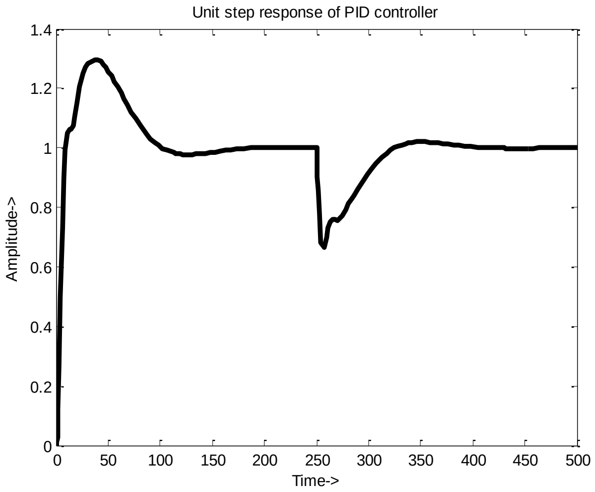

Fig. 8. Unit step response of system using PID controller tuned using Z-N Method compensating for step disturbance

The unit step response of controller compensating the pulse load disturbance of 50% duty cycle originating from 250 sec is shown in figure 9. In this case, the controller has slightly high peak overshoot of 34.72%.

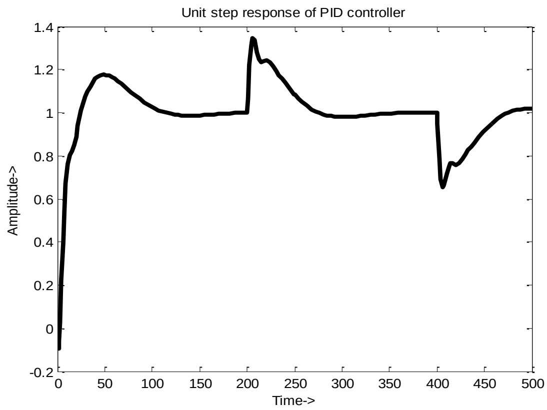

Fig. 9. Unit step response of system using PID controller tuned using Z-N Method compensating for pulse disturbance

From the above results it is observed when controller does the set point tracking operation, the peak overshoot is small and when it is used for load disturbance rejection, the peak overshoot increases. Table I summarizes the results of PID controller transient performance.

TABLE I. PID CONTROLLER TRANSIENT PERFORMANCE

Controller	% Overshoot	Settling Time (sec)	Peak Time (sec)
PID (Pulse disturbance rejection)	34.72%	453.14	205.85
PID (Step disturbance rejection)	29.56%	307.248	37.59
PID (Set point tracking)	17%	86.04	48.92

To qualitatively analyses controller performance, different error indices are used. Widely used error indices are

$$IAE = \int_0^\infty |e(t)| dt \quad (8)$$

$$ITAE = \int_0^\infty t|e(t)| dt \quad (9)$$

$$ISE = \int_0^\infty e^2(t) dt \quad (10)$$

$$ITSE = \int_0^\infty te^2(t) dt \quad (11)$$

Table V indicates error indices of PID controller using Z-N tuning and PID controller using PSO.

TABLE II. ERROR INDICES

Controller	IAE	ISE	ITAE	ITSE
PID Pulse disturbance rejection	7.67	0.42	1346	36.09
PID Step disturbance rejection	5.89	0.31	709.4	18.4
PID Set point	3.93	0.31	131.8	3.98

PSO is used to find the optimal values of PID controller parameters. Tuning of PID using PSO is described in section III. The set point tracking feature of PSO tuned PID controller is shown in figure 10. The overshoot of PSO tuned PID controller is 0% and settling time is little higher at 206 sec.

TABLE III. COMPARISON BETWEEN TRADITIONAL PID CONTROLLER AND PSO TUNED PID CONTROLLER

Controller	K_p	K_i	K_d
PID (Z-N Tuning)	10	0.38	150
PID (PSO Tuning)	0.0788	0.0099	0.0058

From the above table, transfer function for Z-N tuned PID controller is shown as

$$G_c(s) = 10 + \frac{0.38}{s} + 150s \quad (12)$$

Transfer function of PSO tuned PID controller is

$$G_c(s) = 0.0788 + \frac{0.0099}{s} + 0.0058s \quad (13)$$

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PID AND PSO-TUNED PID CONTROLLER TRANSIENT PERFORMANCE

Controller	% Overshoot	Settling Time (sec)
PID (Pulse disturbance rejection)	34.72%	453.14
PID (Step disturbance rejection)	29.56%	307.24
PID (Set point tracking)	17%	86.04
PID PSO	0%	206

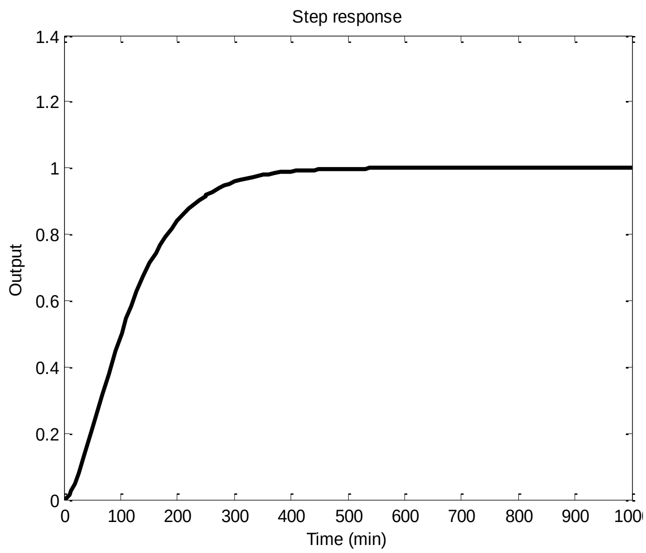

Fig. 10. Unit step response of system with PID controller tuned using PSO

TABLE IV. ERROR INDICES OF PID AND PSO TUNED PID

Controller	IAE	ISE	ITAE	ITSE
PID Pulse disturbance rejection	7.67	0.42	1346	36.09
PID Step disturbance rejection	5.89	0.31	709.4	18.4
PID Set point	3.93	0.31	131.8	3.98
PID PSO tuned	2.85	0.14	106.8	2.54

Table IV shows overall comparison of transient performance of PID and PSO tuned PID controller whereas table V shows the error indices of the respective controller.

V. CONCLUSION

Heat exchanger is one of the most widely used device in chemical industry. Temperature control of heat exchanger is one of the important control aspects. PID controller is used for temperature control. This paper implements a PID controller to control the outlet temperature of heat exchanger using Z-N tuning and PSO tuning. Extensive simulation results and analysis proves that in PSO tuned PID controller, the overshoot is small but the settling time is more.

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AUTHOR PROFILE

Sapna Gupta is with department of Electronics Engineering, University College of Engineering, Rajasthan Technical University, Rajasthan, India. Her research interests include control system and soft computing

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Dr. Rajeev Gupta was born in Mathura, India on 1st July 1965. He obtained his B.E. (Electrical Engineering) from University of Rajasthan in 1986. He obtained his M. Tech (Control and Instrumentation Engineering) and Ph.D from Indian Institute of Technology, Bombay in 1995 and 2004 respectively. He is currently working as Professor in Electronics Engineering and Director of University College of Engineering, Rajasthan Technical University, Kota (India). His research interests are in power system stabilizers, periodic output feedback, multi-rate output feedback techniques and model reduction methods, PSO, Fuzzy control and Soft computing and Intelligent Control.

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