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Enhancement of Heat Exchanger Control Using Improved PID Controller

Gopalakrishna G., Sivakumaran N. and *Sivashanmugam P.

Modelling and Simulation Research Laboratory, Department of Chemical Engineering,
National Institute of Technology, Tiruchirappalli-620 015, India

Fax: +91 431 2500133

*E-mail: psiva@nitt.edu

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Abstract: The Proportional, Integral and Derivative (PID) controllers are widely used in industrial applications. Their popularity comes from their robust performance and also from their functional simplicity. Temperature control of double tube heat exchanger system is presented and ant colony algorithm for optimizing PID parameters of temperature controller is presented in this paper on the basis of conventional PID controller. Temperature controller based on ant colony optimization for double tube heat exchanger is designed. Simulation results show that, for the case of heat exchanger system, ACO-PID is good model and generalize well. The closed loop unit step response obtained with the proposed PID compares favorably with the one achieved using a conventional PID controller with dynamic closed-loop simulation. More important, the proposed approach takes a fraction of the time spent by the standard technique, without the need of perturbing the closed-loop system. *Copyright © 2009 IFSA.*

Keywords: PID controller, Ant colony optimization, Foraging, Combinatorial optimization

1. Introduction

Heat exchangers are one of the simplest and important units in process industries. The success of any plant depends on the performance of each and every unit of that plant. Heat exchanger performance affects the total plant operation directly. Controlling the heat exchanger system properly by the principles of automatic control and optimization theory is very important to build a plant with good performance. Control using PID controllers, compared to other methods, is more effective and economical. The heat exchanger system has highly nonlinear features. When the operating point changes a little, the dynamic performance of the system may change a lot. For this reason, controller of

heat exchanger needs to respond accordingly and work well under different operating points. The key of a PID controlling system is an optimal design of PID parameters. It affects the controlling effect directly.

It was recently estimated that more than 90 % of all control loops involve PID controllers [1]. In the control of dynamic systems, no controller has enjoyed both the success and failure of the PID control. ID controller is a well known technique and extensively used in the process industries [2-3].

What is a PID controller? The acronym PID stands for Proportio-Integro-Differential control. The popularity of the PID controller is due to their simplicity-it has only three adjustable parameters, transparency of PID control mechanism, robust performance in a wide range of operating conditions, the availability of a large number of highly efficient, reliable, and cost effective commercial PID control modules and their acceptance from the operators are among the reasons for their success [2].

The design of such a controller requires specification of those parameters: proportional gain (K_P), integral time constant (K_I), and derivative time constant (K_D). It has been a crucial problem to tune properly the gains of PID controllers because many industrial plants are often burdened with the characteristics such as high order, time delays and nonlinearities [4]. Traditionally, the problem has been handled by a trial and error approach. Design engineers must tune PID controllers manually and usually take considerable time.

For the last 50 years, various formulations for a more systematic approach to reduce the time spent on optimizing the choice of the three controller parameters have been developed. Actually, the development of PID tuning rules has been one of the major areas of research about the PID controller. The Zeigler-Nichols tuning formula (Zeigler & Nichols, 1942) is the original work from Zeigler and Nichols, perhaps is the best known tuning method [5]. Their method determines the parameters by observing the gain at which the plant becomes oscillatory and the frequency of this oscillation. When the PID controller parameters are tuned by ZN, the closed loop system's response can present an overshoot up to 25 %. Several other similar simple methods have been developed (ex. [6]-[8]). Macgregor et. al. (1975) for example suggests a method to obtain the optimal gains from the plots of contour variances under PID feedback control [9]. The resulting controller can be seen as a LQG type. The PID design based on the optimal linear quadrant theory was also discussed in Argelaget (1995) [10]. Panagopoulos et. al. Presented a design method for PID controllers based on optimization of load disturbance rejection with constraints on robustness to model uncertainties [11]. Bilinear transformation and linear programming are used to determine the set of all PID gains that can stabilize a given discrete- time plant of arbitrary order [12]. On the other hand, Vu (1992) [14] gives an iterative algorithm that arises from a Riccati-like equation to obtain the PID parameters that minimize the output variance of the closed-loop system. Grassi et. al [15] presented a frequency loop shaping methods based on sensitivity function for tuning PID controllers. Considering the limitations of the Zeigler-Nichols formulae and some empirical techniques in raising the performance of PID controller and to reduce the complexity of tuning PID parameters by the traditional approaches, several new methods, such as the genetic algorithm [16]-[18], fuzzy logic [19]-[24], neural network [25], pattern recognition [26] have been developed to tune the parameters of the PID controllers. In these studies, it has been shown that these approaches have a well solution in tuning the parameters of PID controllers. However, there are always short comings. For example, limiting the searching range, slow convergence, the initial value depends on the project experience and other conditions. There are several reasons to develop better methods to design PID controllers. One is the significant impact it may give because of the wide spread use of the controllers. The other is the enhancing performance of the PID controllers can derive from improved design methods.

The approach presented here aims to minimize the problems faced as stated earlier, by applying a prominent algorithm by treating the design problem of PID controller as an optimization problem. The

problem formulation adopts four performance indexes: the maximum overshoot, the settling time, the rise time, and the integral absolute error of step response as the objective function to determine the parameters of the PID controller for getting a well performance under a given plant. In this study the primary design goal is to obtain good load disturbance response by minimizing the integral absolute control error. At the same time the transient response is guaranteed by minimizing the other three performance indexes. For this problem solution is proposed using an algorithm based on Ant Colony Optimization technique. ACO is a novel simulated evolutionary algorithm that has been recently developed and draws more and more attraction of scholars by its prominent advantages such as parallelism, positive feedback, robustness, quick convergence, getting the global optimal solution easily etc [27]-[29]. It is a general purpose optimization technique and it is proved effective for combinatorial optimization problems such as hydro electric generation scheduling problem [30], traveling salesman problem [31], graph coloring problem [32] with successful results. These are some of the features of the presenting technique that differentiate other methods:

1. It can be implemented easily,
2. It allows a more flexible problem formulation,
3. Global optimal solution can be achieved very easily.

Moreover, the simulation results of the ACO-PID controller is compared with the other traditional methods to examine whether the ACO-PID controller has a better control performance.

2. Heat Exchanger System

The heat exchanger dynamical equations can be expressed in the following form [33]:

$$\omega_c \rho_c c_c (T_i - T_o) + UA(T_c - T_o) = V_c \rho_c c_c \frac{dT_o}{dt} \quad (1)$$

$$\omega_h \rho_h c_h (T_v - T_c) - UA(T_c - T_o) = V_h \rho_h c_h \frac{dT_c}{dt} \quad (2)$$

T_i	Inlet temperature of cold water, °F
T_o	Outlet temperature of cold water, °F
T_v	Inlet temperature hot water, °F
T_c	Outlet temperature of hot water, °F
ω_c	Flow rate of cold water, lb/time
ω_h	Flow rate of hot water, lb/time
V_i	Volume
P_i	Density
c_i	Specific heat
A	Area of cross-section of heat exchanger
U	Heat transfer co-efficient

The model equations given above are derived from first principles. The dynamics described by equations (1) and (2) correspond to a double tube heat exchanger system. The objective is that the output temperature of the cold fluid ' T_o ' to track the step input change in hot fluid inlet flow rate ' ω_h '.

3. Problem Formulation

The transfer function of a PID controller is defined as

$$G_c(S) = K_p + \frac{K_i}{s} + K_d S \quad (3)$$

where, K_p , K_i and K_d are the proportional, integral and derivative gains respectively. The ant colony algorithm generates the PID controller ($G_c(S)$) parameters i.e. K_p , K_i and K_d . This is illustrated in Fig 1. The error ($E(s)$) forms the input to the PID controller and $U(s)$ for the heat exchanger plant ($G(S)$). The $E(S)$ is the error between the reference input $R(S)$ and the output $C(S)$. For a given plant, the problem of designing a PID controller is to adjust the gains (K_p , K_i and K_d) of the controller for getting desired response.

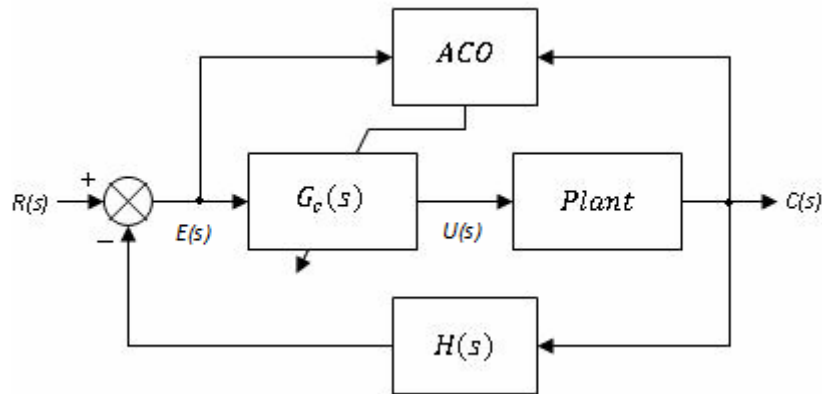


Fig. 1. ACO-PID control system.

It is very important for any control system to maintain its transient-response within tolerable limits or prescribed limits. Hence, the transient-response characteristics of a control system to a unit-step input are specified by using the following performance indexes that characterize the performance of the PID control systems:

1. Settling time, t_s : The settling time is the time required for the response curve to reach and stay within a range about the final value of size specified by absolute percentage of the final value. The settling time is related to the largest time constant of the control system.

$$f_{st} = t_s$$

2. Maximum overshoot, M_p : The maximum overshoot is the maximum peak value of the response curve measured from unity.

$$f_{mo} = C_{max} - C(t_s)$$

The amount of the maximum overshoot directly indicates the relative stability of the system.

3. Rise time, t_r : the rise time is the time required for the response to rise from 10 % to 90 % of its final value.

$$f_{rt} = t_r$$

In summary, the optimal design of PID controllers can be formulated in the following way:

For a given plant, find the parameters K_p' , K_i' and K_d' of the PID control system that minimizes the transient response specifications, i.e. minimize

$$f = f_{st} + f_{mo} + f_{rt} \quad (4)$$

4. Ant Colony Optimization Algorithm

Ant colony optimization is a population-based metaheuristic that can be used to find approximate solutions to difficult optimization problems [34]. It is inspired by the foraging behaviour of ant colonies. In ant colony optimization (ACO), a set of software agents called "artificial ants" search for good solutions to a given optimization problem transformed into the problem of finding the minimum cost path on a weighted graph. The artificial ants incrementally build solutions by moving on the graph. The solution construction process is stochastic and is biased by a pheromone model, that is, a set of parameters associated with graph components (either nodes or edges) the values of which are modified at runtime by the ants. ACO has been applied successfully to many classical combinatorial optimization problems, as well as to discrete optimization problems that have stochastic and dynamic components. Examples are the application to routing in communication networks and to stochastic version of well-known combinatorial optimization problem, such as the probabilistic traveling salesman problem. Moreover, ACO has been extended so that it can be used to solve continuous and mixed-variable optimization problems. Ant colony optimization is probably the most successful example of artificial/engineering swarm intelligence system with numerous applications to real world problems.

The ants construct the solutions as follows. Each ant starts from a randomly selected city (vertex of the construction graph). Then, at each construction step it moves along the edges of the graph. Each ant keeps a memory of its path, and in subsequent steps it chooses among the edges that do not lead to vertices that it has already visited. An ant has constructed a solution once it has visited all the vertices of the graph. At each construction step, an ant probabilistically chooses the edge to follow among those that lead to yet unvisited vertices. The probabilistic rule is biased by pheromone values and heuristic information, the higher the pheromone and the heuristic value associated to an edge, the higher the probability an ant will choose that particular edge. Once all the ants have completed their tour, the pheromone on the edges is updated. Each of the pheromone values is initially decreased by a certain percentage. Each edge then receives an amount of additional pheromone proportional to the quality of the solutions to which it belongs (there is one solution per ant). This procedure is repeatedly applied until a termination criterion is satisfied.

The first step for application of ACO for a combinatorial optimization problem consists of in defining a model of the combinatorial optimization problem as a triplet $\{\mathcal{S}, f, \Omega\}$, where:

- \mathcal{S} is a search space defined over the finite set of discrete decision variables.
- $f: \mathcal{S} \rightarrow \mathcal{R}_0^+$ is an objective function to be minimized.
- Ω is a set constraint among the variables.
- The search space \mathcal{S} is defined as follows: A set of discrete variables x_i with values $v_i^j \in \mathcal{D}_i = \{v_i^1, \dots, v_i^{|\mathcal{D}_i|}\}$ where $i = \{1, \dots, n\}$ given. Elements of \mathcal{S} are full assignments, that

is assignments in which each variable x_i has the value v_i^j assigned from its domain \mathcal{D}_i . The set of feasible solutions \mathcal{S}_Ω is given by the elements of \mathcal{S} that satisfy all the constraints in the set Ω .

A solution $s^* \in \mathcal{S}_\Omega$ is called a global optimum if and only if $f(s^*) \leq f(s) \forall s \in \mathcal{S}_\Omega$. The set of all global optimum solutions is denoted by $\mathcal{S}_\Omega^* \subseteq \mathcal{S}_\Omega$. Solving a Combinatorial optimization problem requires finding at least one $s^* \in \mathcal{S}_\Omega$.

In ACO, artificial ants build a solution to a combinatorial optimization problem by traversing a fully connected construction graph, defined as follows. First, each instantiated decision variable $X_i = v_i^j$ is called a *solution component* and denoted by c_{ij} . The set of all possible solution components is denoted by \mathcal{C} . Then the construction graph $G_C(V, E)$ is defined by associating the components \mathcal{C} either with the set of vertices V or with the set of edges E .

A pheromone trail value τ_{ij} is associated with each component c_{ij} . Pheromone values allow the probability distribution of different components of the solution to be modeled. Pheromone values are used and updated by the ACO algorithm during the search.

The ants move from vertex to vertex along the edges of the construction graph exploiting information provided by the pheromone values and in this way incrementally building a solution. Additionally, the ants deposit a certain amount of pheromone on the components, that is, either on the vertices or on the edges that they traverse. The amount $\Delta\tau$ of pheromone deposited may depend on the quality of the solution found. Subsequent ants utilize the pheromone information as a guide towards more promising regions of the search space.

The metaheuristic consists of an initialization step and of three algorithmic components whose activation is regulated by the Schedule Activities construct. This construct is repeated until a termination criterion is met. Typical criteria are a maximum number of iterations or a maximum CPU time.

5. Applying ACO to The PID Controller Design Problem

The objective of an optimal design of PID controller for a given plant is to select the best parameters K_p , K_i and K_d of the controller such that the specifications of the transient response meet the desired values [35]. The design of the PID problem can be represented as a graph problem for applying ACO.

In this work, each parameter of K_p , K_i and K_d is coded by 4000 random numbers respectively and with a resolution of 0.001 among each number. Each set of number for particular parameter represents a solution value of the parameters K_p , K_i and K_d . Choosing more number nodes and small resolution value between each number for more accuracy.

The following section describes the development of Ant Colony based algorithm for PID controller design. Various steps involved are explained below:

Step 1: Deploying ants initially

The initial step involved is deploying the ants in a feasible solution space randomly. Here, position of an ant refers to one complete solution set to the problem. In this work, there are three variables to be optimized namely K_p , K_i and K_d . Here, the location of an *ant* is the point in the three dimensional

space having co-ordinates K_p, K_i and K_d for generality, let the ants be described as $a_1, a_2, \dots, a_k, \dots, a_n$ where n is the ant population size. For $n = 4$, initial random position of ants is shown in Fig 2.

Step 2: Evaluation of Objective function value

The random values of K_p, K_i , and K_d corresponding to each ant is now substituted in mathematical model of the plant and the rise time (t_r), settling time (t_s), peak overshoot (P_o) and steady state error (e_{ss}) of each ant position is evaluated. The objective function value of j^{th} ant in the t^{th} iteration is taken as,

$$f = f_{st} + f_{mo} + f_{rt} \quad (5)$$

Step 3: Computation of pheromone content at ant locations

In this step, the pheromone content at each ant location is computed; the pheromone content at j^{th} location at t^{th} iteration is given as:

$$\tau_j(t) = (1 - \rho) * \tau_j(t-1) + \frac{1}{F_j(t)} \quad (6)$$

In the above equation,

ρ is the evaporation constant generally taken between 0 and 1 and $\tau_j(t-1)$ is the pheromone level at j -th location at its previous stage of ant movement.

The value of ρ is taken by trial and error to achieve better solution with lesser number of iterations. When this value is kept at unity, it shows that there is complete and spontaneous evaporation of pheromone, which is not true in nature. When the value of ρ is made at zero, there is no evaporation at all, which is also not true. Hence, depending on each problem, a suitable value of ρ is required. In Fig 3 shaded circles indicate value of pheromone of each ant. For clarity, the size of circle is taken as a measure of pheromone content. The location visited by each ant and the pheromone content at the locations are stored in a Tabu list. The memory required for the Tabu list depends on ant population size as well as number of movements made by the ants. In general, if there are n ants making m movements, the size of Tabu list is mxn .

Step 4: Computation of movement probability

The ants are dispatched based on the level of pheromone content at its location and *movement probability*, (p_m). A number between 0 and 1 is randomly generated which is termed as *threshold probability* p_t . Now the *movement probability*, p_j of an ant at j -th location is computed using equation (7).

$$p_m = \frac{\tau_j^m}{\sum_1^n \tau_j} \quad (7)$$

In equation (7), the order of pheromone, m is kept at unity for computational simplicity.

Fig. 4 shows movement probability for all four ants.

Step 5: Ant dispatch

For $p_j \geq p_t$, then the ant is in a *promising region of the solution space* and hence, the ant moves to a new position governed by equation (8).

$$\alpha_{new} = \alpha_{old} + R_1 \angle \theta_1 \quad (8)$$

This step is demonstrated in Fig. 5. Here, an ant compares pheromone content at its location with that of the remaining ants whose $p_j \geq p_t$ and moves towards locations of higher pheromone deposition. In Fig. 5, pheromone of a_1 is lower than that of a_3 and a_4 . Hence, ant a_1 now moves a distance R_1 along OB and reaches point, D. The direction of ant movement or angle θ_1 is obtained through the vector addition of OA and AB where OA is towards a_4 and AB is towards a_3 . Similarly, ant a_4 moves a distance, R_1 towards a_3 and reaches point, E. The ant a_3 having largest pheromone content remains in its position. The variable R_1 is newly introduced in this algorithm and is termed as the step length of movement of the ants.

Else

Go to step 6.

Step 6:

For $p_j < p_t$, then the ant is in a *less favorable region of the solution space* and the ant movement is given by equation (9).

$$\alpha_{new} = \alpha_{old} + R_1 \angle \theta_2 \quad (9)$$

This is illustrated in Fig. 6. Now all the ants in this region move a distance, R_1 , towards the centroid, C of cluster of all other ants, whose $p_j \geq p_t$. Thus ant, a_2 moves towards C and reaches the point, F. This step prevents divergence of the algorithm.

When all ants complete the steps 2 to 6, it is termed one iteration. The final position of all ants after iteration is shown in Fig. 7.

It is important to mention that angles θ_1 and θ_2 are governed by position of other ants and this concept mimics the behavior of real ants whose movements are influenced by pheromone trails left by the other ants.

Step 7: End the program if termination criterion is reached; else go to step 2.

The termination criterion can be in two ways; either by ending the program when objective function value reaches a reasonably low value or after a finite number of iterative steps. In the present case, the program was terminated after specified iterations.

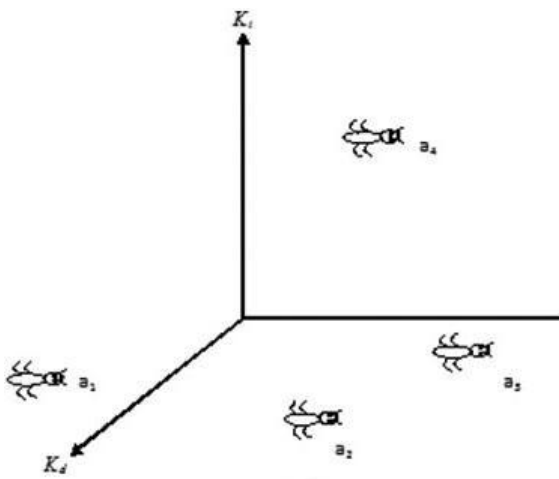


Fig. 2.

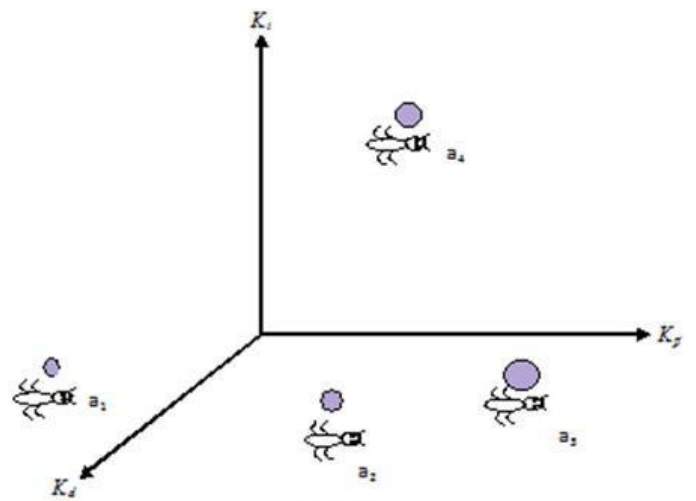


Fig. 3.

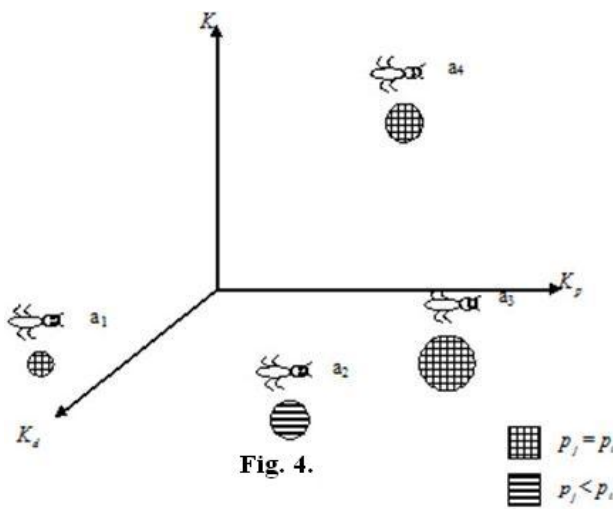


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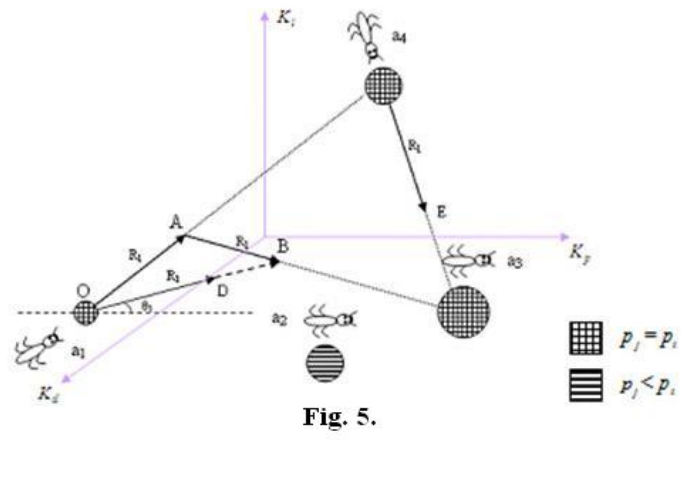


Fig. 5.

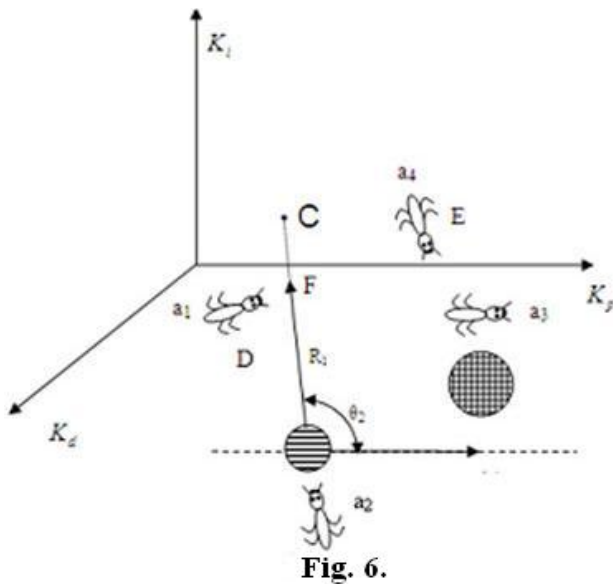


Fig. 6.

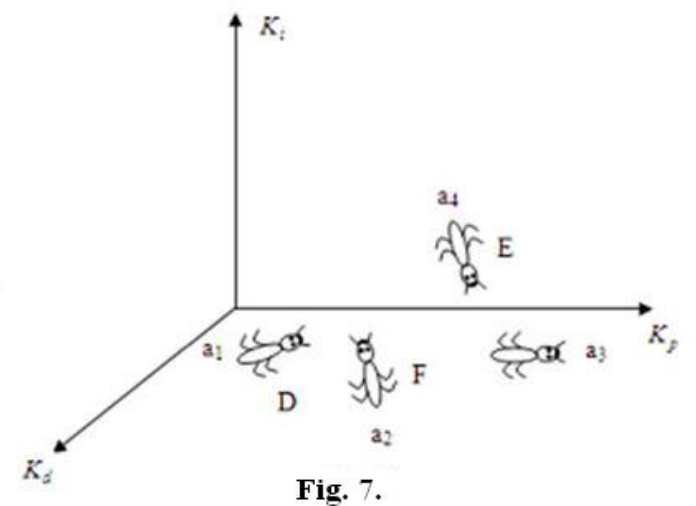


Fig. 7.

6. Simulation Results

The parameters used in the simulation are [36]:

F_c	1 ft ³ /min
F_h	1.5 ft ³ /min
UA	183.9 Btu/°F.min
V_c	10 ft ³
V_h	25 ft ³
ρ_c, ρ_v	1

T_i	50 °F
T_o	125 °F
T_v	200 °F
T_c	150 °F
$\rho_c C_c$	61.3 Btu/°F.ft ³
$\rho_v C_v$	61.3 Btu/°F.ft ³

The block diagram representation of the heat exchanger system is shown in Fig. 8. The transfer function of the system with outlet cold fluid temperature to the input hot fluid flow rate is given by (after linearizing around the operating point by using Taylor series expansion):

$$\frac{C(S)}{U(S)} = \frac{16.6667}{27.7777S^2 + 16.1111S + 1}$$

The ACS algorithm was implemented by developing a dedicated software using MATLAB. The parameters of ACS are taken by trial and error to yield best solution. The parameters used in this work are listed below:

Ant population size	10
Evaporation constant, ρ	0.7
Initial pheromone content, $\tau(t - 1)$	0.0
Visibility, η	1.0
Visibility enhancement factor, β	1.0
Number of ant movements	100

Fig. 9 shows the variation of the objective function for the above mentioned system.

Table 1 summarizes the simulation results of the ACO-PID controller performance on the Heat exchanger system.

Table 1. Summary of the simulation results.

Dynamic response Specification	PID Controller Design_method		
	ZN	ANN	ACO
Rise time	16 sec	2 sec	0.9 sec
Peak overshoot	18 %	2 %	1 %
Settling time	50 sec	6 sec	1.62 sec
Steady state error	0	0	0

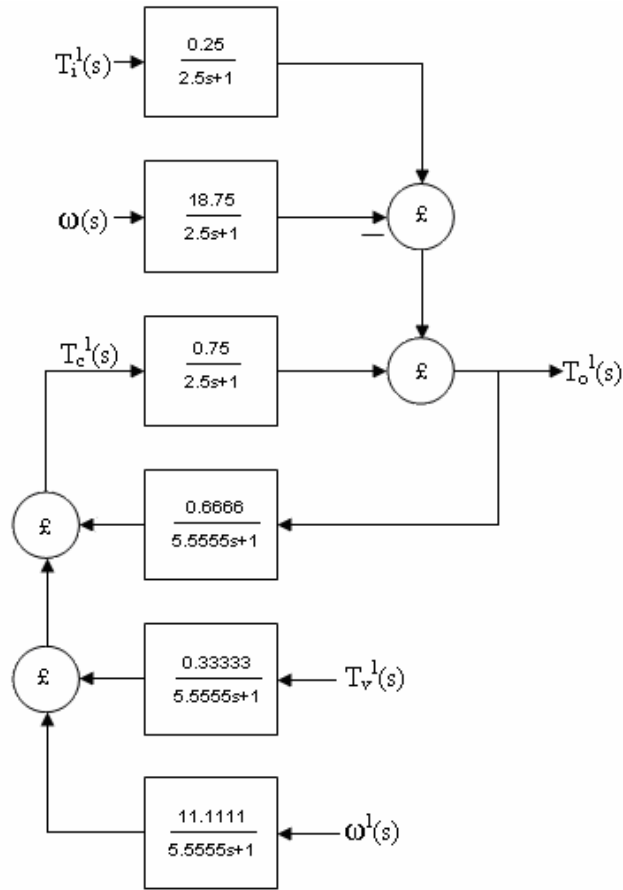


Fig. 8. Block diagram representation of the Heat Exchanger system.

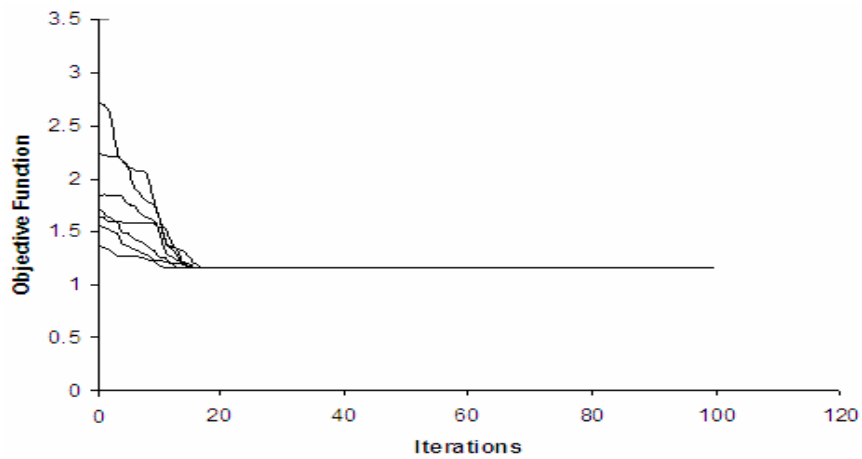


Fig. 9. Variation of objective function all ants.

Fig. 10 shows the step response of the heat exchanger system. The results obtained by using Zeigler-Nichols and ANN method are also presented for comparison. Observing the performance indexes in Table 1, we can find that the ACO-PID controller has excellent unit-step response for this system considered. Obviously, we can conclude that the proposed method well improves the optimal tuning problem of PID controllers for heat exchanger system considered.

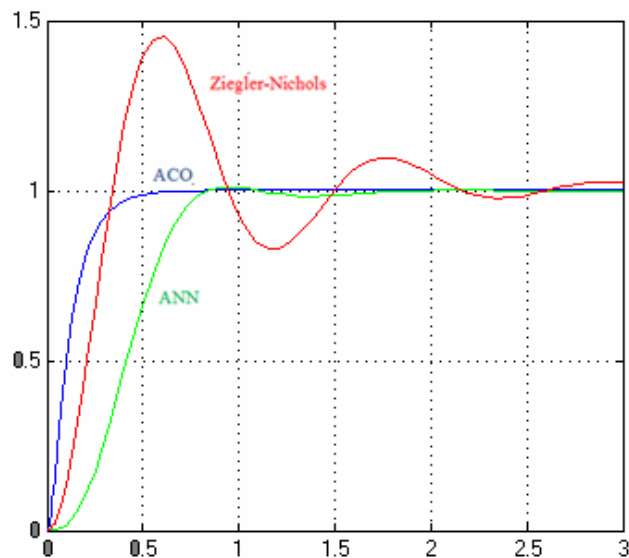


Fig. 10. Comparison of unit-step responses.

7. Conclusions

This work presents a new intelligent optimal design method for the tuning problem of PID controllers for Heat exchangers based on ACO-PID algorithm. The problem of tuning PID controllers is formulated as an optimization problem considering three performance indexes of transient response, the maximum overshoot, settling time and rise time. By using ACO a solution algorithm is developed and implemented. For comparison PID controllers designed by use of existing techniques such as ANN are implemented and has been shown by simulation the promising feature of proposed method.

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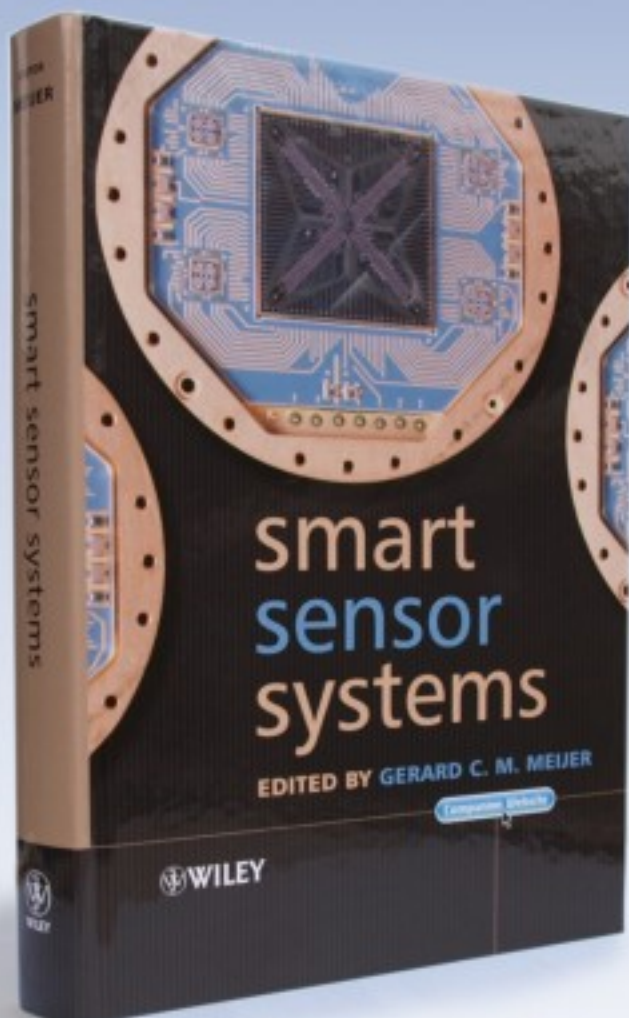
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