

On-Line Auto-Tuning Robust Nonlinear Neural PID Controller Design for Double-Pipe Heat Exchanger Based on Particle Swarm Optimization

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Abstract: *The heat exchanger systems have highly nonlinear features between its variables and time delay. In addition, the parameters of them change constantly during operation. Therefore, the heat exchangers need nonlinear robust controller for obtaining required outlet temperature under all operating conditions.*

In this paper, a robust nonlinear neural PID (NLNPID) controller is proposed for temperature control of double-pipe heat exchanger. Particle swarm optimization (PSO) technique is used to determine on line auto tuning the optimal parameters of proportional-integral-derivative (PID) controller. Mathematical model of heat exchanger takes into account the changes in the density, thermal conductivity, viscosity, specific heat and convection heat transfer coefficient of the fluid which are resulting from changing in temperatures and the velocities with classical PID control. Simulations results show that the performance of the NLNPID controller produces good responses features and give desired outlet

temperature under all operating conditions without over shoot and fluctuating.

Keywords: *heat exchanger, nonlinear, PID, PSO*

1-Introduction

Heat exchangers are one of the most equipment widely used in chemical plants and units of production and processing of oil and gas. These exchanges are used either in cooling or heating fluid at different temperatures to suit the industrial purpose which are found for it.

Controllers are used to control the temperature of the fluid in order to enable the heat exchanger to give the desired temperature at different working conditions. Heat exchangers are exposed to many changes during its work as precipitation and erosion and change the speed of the flow of the fluid and change Physical properties of the fluid.

Classical controllers' (like PID) response to changing conditions of work and operation are not robust, which leads to lack of temperature control. For this reason, controller of heat exchanger needs to respond accordingly and work well under different operating process.

The PID controller is more effective compared with other controller structure and still use in many practical applications in different fields, and researchers tried to increase the robustness of theses controllers by made its gains adaptive with variations of work condition of the systems. So the industrial plants have problems such as high order, time delays, nonlinearities; and changing in system variables and parameters [1]. Therefore, it has been quite difficult to tune properly the gains of PID controllers. So there are many algorithms to tune the parameters of the PID controller in order to avoid these problems in the prosperities of systems: Genetic Algorithms [2], Fuzzy Logic Control [3,4], Neural Network[5,6] have been used to make PID more robust. In recent

years, Particle Swarm Optimization (PSO) entered strongly as a method for determining the optimal parameters of proportional-integral-derivative (PID) controller [1, 7, 8, 9]. The PSO methods have been employed successfully to solve complex optimization problems. Generally, PSO is characterized as a simple concept, easy to implement, and computationally efficient. Unlike the other heuristic techniques, PSO has a flexible and well-balanced mechanism to enhance the global and local exploration abilities [10].

In this paper a PSO is used as a simple steps algorithm and fast tuning the parameters of the nonlinear neural PID (NLNPID) controller for temperature control of a double pipe heat exchanger.

Within the limits of what has been viewed, it was found that the published research considers the properties of fluids in the heat exchanger constant at work, for example, see [11,12,13] and this is something unrealistic. Physical properties of the fluids change with the temperature and the velocity of the fluid. The proposed mathematical model in this paper takes into account these changes to the production model of the control system more realistic.

The contribution of this work is to present a controller able to treat with nonlinearity of heat exchanger and variation of its parameters during operation and give desired outlet temperature response without over shoot and steady state error. Also, the controller action do not exceed logical limit of the solenoid valve.

2- Nonlinear Heat Exchanger Mathematical Model

Unsteady-state energy balances have been used as the basis for the derivation of the mathematical model for the double pipe heat exchanger. Cold water flows through the outer pipe and it is being heated by hot water that flows in inner pipe as shown in figure (1)

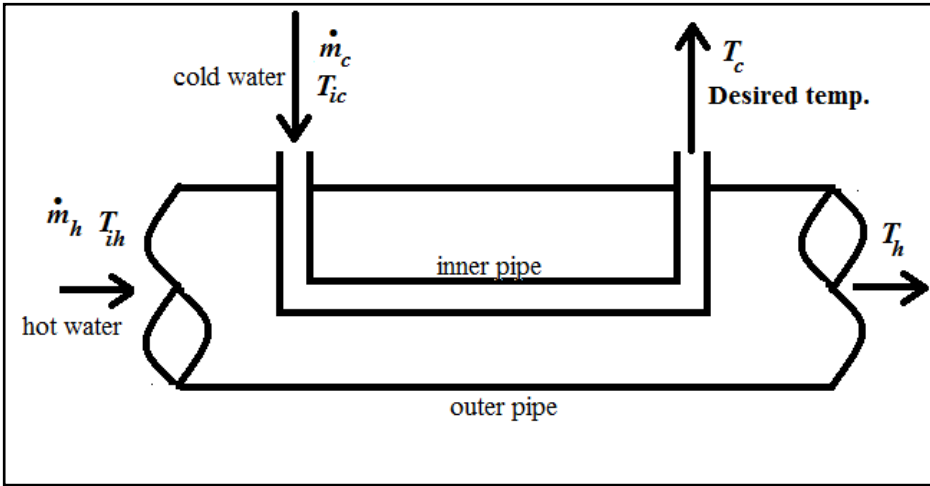


Figure (1): Double pipe heat exchanger

The mathematical model of the system described as below [14]:

$$C_h \dot{T}_h = \dot{m}_h c_h (T_{ih} - T_h) - \frac{1}{R} (T_h - T_c) \quad (1)$$

$$C_c \dot{T}_c = \dot{m}_c c_c (T_{ic} - T_c) + \frac{1}{R} (T_h - T_c) \quad (2)$$

Where R is thermal resistance and can be calculated as follow:

$$R = (1/(h_h A_i)) + (\ln(D_o/d_i)/(2\pi k_w L)) + (1/(h_c A_o)) \quad (3)$$

The objectives of the solution of the heat exchanger model is to specify the outlet temperature response (T_c) of the cold fluid which is resulting from the step input change in hot fluid inlet flow rate (\dot{m}_h). Equations (1&2) are nonlinear because the state variable (T_h) is multiplied by the control input (\dot{m}_h).

In previous references, the term ($T_{ih} - T_h$) is assumed constant for purposes of linearized model and this is not reality.

The temperature will change with time until it reaches the steady-state. This change affects in the physical properties of the fluids used in exchange, therefore must be taken that into consideration.

The changing in the physical properties in terms of the temperature is entered into the mathematical model of heat exchanger, as shown in the equations below. The properties of water are estimated with the aid of equations listed in equations (4) to (7) having a maximum deviation of 3.5 % applicable in the range $0 \leq T \leq 100$ where T is the temperature of water in $^{\circ}C$ [15].

$$\rho = 1000 \left[1 - \frac{(T - 4)^2}{119000 + 1365T - 4T^2} \right] \quad (4)$$

$$k = 0.56112 + 0.00193T - 2.60152749e-6T^2 - 6.08803e-8T^3 \quad (5)$$

$$\mu = 0.00169 - 4.25263e-5T + 4.9255e-7T^2 - 2.09935e-9T^3 \quad (6)$$

$$c = 4217.629 - 3.20888T + 0.09503T^2 - 0.00132T^3 + 9.415e-6T^4 - 2.5479e-8T^5 \quad (7)$$

Also, the value of heat transfer coefficient (h) depends directly on its temperature and the speed of the fluid and as shown in the following equations:

$$Pr = C\mu / k \quad (8)$$

$$Re = 4 \dot{m}_h / (\mu \pi d_i) \quad \text{for inner flow} \quad (9)$$

$$Re = 4 \dot{m}_c / (\mu (\mu \pi (D_i + D_o))) \quad \text{for outer flow} \quad (10)$$

The average Nusselt number for developing laminar flow in circular pipe is determined from [16]

$$Nu = 1.86 \left(\frac{Re Pr D}{L} \right)^{\frac{1}{3}} \left(\frac{\mu}{\mu_s} \right) \quad (11)$$

Where D is hydraulic diameter,

$$D = d_i \text{ for inner flow } \& \quad D = D_o - D_i \text{ for outer flow.}$$

For turbulent flow [16]

$$Nu = 0.023Re^{0.8} * \rho r^n \quad (12)$$

Where $n = 0.4$ for heating and 0.3 for cooling of the fluid flow through the pipe.

$$h_h = Nu_k / d_i \quad \text{for inner flow} \quad (13)$$

$$h_c = Nu_k / (D_o - D_i) \quad \text{for outer flow} \quad (14)$$

From the equations above, it is found that any change in the temperature and the velocity of the fluid during the control process will be influential on the rest of the thermal properties of the fluid; therefore, the process control will be more realistic.

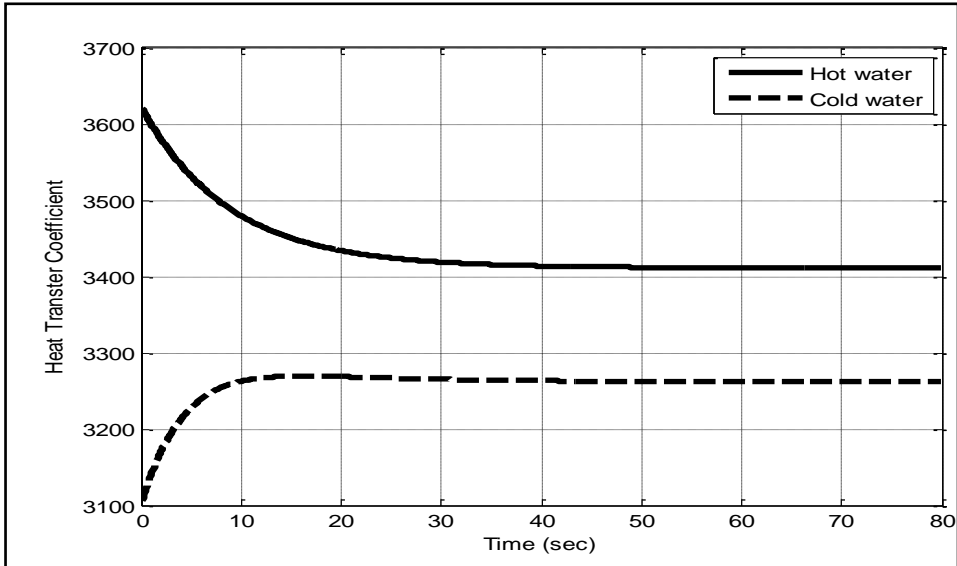
3-Open Loop Analysis

The differential equations (1&2) of the heat exchanger model combined with equations (3 to 14) are solved by Rung - Kutta method and using Matlab program which is written for this purpose. To show how the properties of fluid change with changing in temperature, the step change of hot water flow rate is performed.

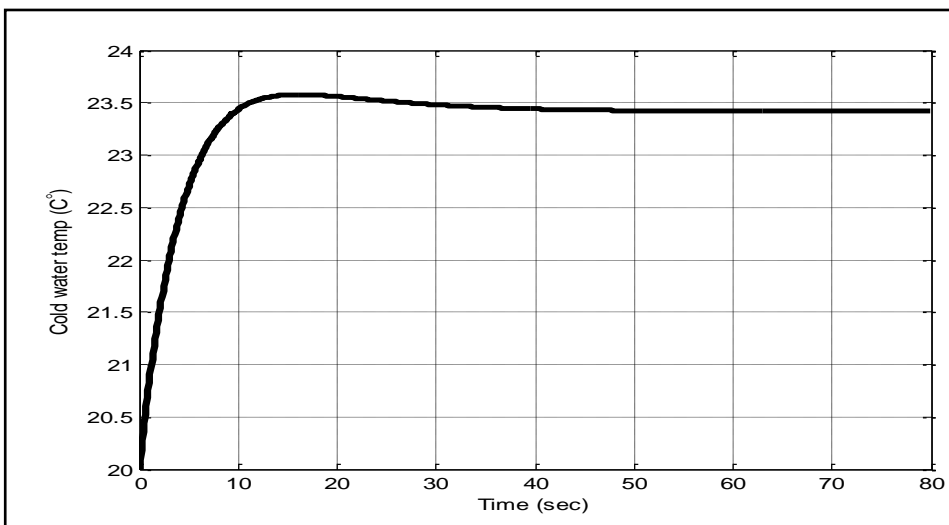
For hot water mass flow rate of 1kg/sec and cold water mass flow rate of 2.5 kg/sec, the change in heat transfer coefficient of hot water (h_i) and cold water (h_o) with respect to time and cold water response are shown in figures (2-a) and (2-b) respectively . It is clear that the value of the (h_i) reduces during the process, while the value of the (h_o) increase till it reach steady states.

Also the changing in the mass flow rate changes the Reynold number and that leads to change the value of Nusselt number and heat transfer coefficient of water. These changing have great effect on the controller performance and make the controller does not give

desired temperature. All these changes in the properties are taken into consideration when designing the present controller.



(a)



(b)

Figure (2): Open loop step response of the heat exchanger

4. Nonlinear Neural PID Controller Design

The controller that is used in this paper is a nonlinear neural PID (NLNPID) controller and its structure is shown in figure (3). It has three gains as in linear PID, K_p , K_i and K_d which are called the proportional gain, the integral gain and the derivative gain respectively.

The present PID control system was consisted of by the classic PID controller and particle swarm optimization (PSO) algorithm, its structure is shown in figure (4). Controller is consisted of two parts, PID controller: direct closed-loop control of controlled outlet temperature and tune PID controller parameters K_p , K_i ; and K_d by (PSO) to give optimization of control performance index according to system operating condition.

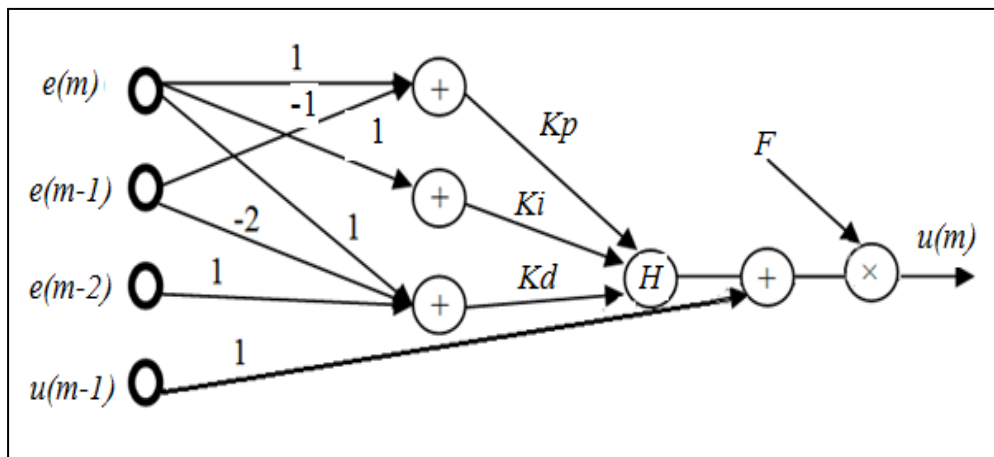


Figure (3): The nonlinear PID neural controller architecture

The proposed control law of the feedback flow rate NLNPID controller as follows:

$$u(m) = (u(m-1) + H(net)) \times F \tag{15}$$

The first calculation within the neuron consists of calculating the weighted sum net of the inputs as follows: [17]

$$net = K_p [e(m) - e(m-1)] + K_i e(m) + K_d [e(m) - 2e(m-1) + e(m-2)] \quad (16)$$

Next the output of the neuron h_n is calculated as the Polywog wavelet function of the net as: [17]

$$h_n = H(net) \quad (17)$$

$$H(net) = (3(net)^2 - (net)^4) e^{-0.5(net)^2} \quad (18)$$

The on-line auto tuning on line PID input vector consists of $e(m)$, $e(m-1)$, $e(m-2)$ and $u(m-1)$, where $e(m)$ and $u(m-1)$ denote the input error signals and the PID output is $u(m)$. In the present work, the control action u is equivalent to mass flow rate of hot water m_h and F is the scale factor.

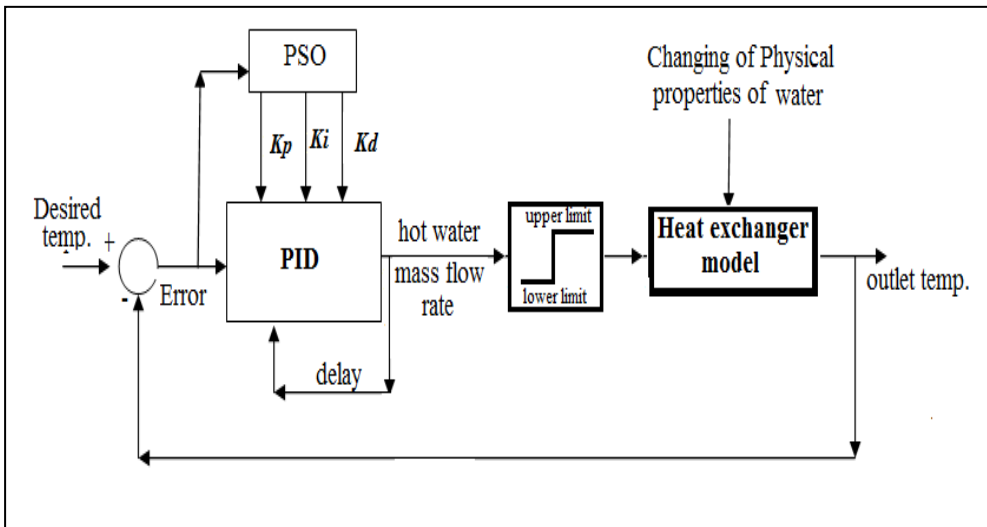


Figure (4): Temperature control system

A nonlinear Polywog wavelet activation functions is used [18] in the structure of the proposed controller, as shown in figure (5).

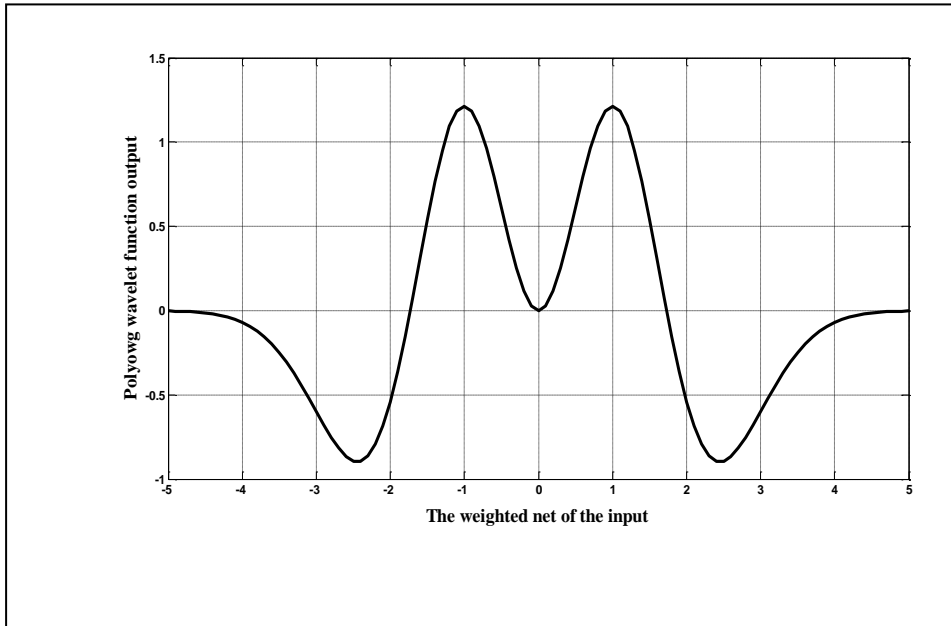


Figure (5): Polywog wavelet function

4.1 Learning Algorithm

The objective of the paper is to use the PSO algorithm in order to obtain on line auto tuning optimal parameters of temperature NLNPID controller of a double-pipe heat exchanger.

At the beginning of PSO solution, a population of particles is initialized with random positions and random velocities. Each particle adjusts its path towards its best solution (fitness) that is achieved so far. This value is called pbest. Each particle also modifies its path towards the best previous position attained by any member of its neighborhood. This value is called gbest. Each particle moves in the search space with an adaptive velocity [18].

The particles are evaluated using a fitness function to see how close they are to the optimal solution [19].

$$V_{r,n}^{m+1} = wV_{r,n}^m + c_1 rand_1 (pbest_{r,n}^m - x_{r,n}^m) + c_2 rand_2 (gbest_n^m - x_{r,n}^m) \quad (19)$$

$$x_{r,n}^{m+1} = x_{r,n}^m + V_{r,n}^{m+1} \quad (20)$$

Where

$V_{r,n}^m$ is the velocity of the rth particle at mth iteration .

$x_{r,n}^m$ is the position of the rth particle at mth iteration.

r is number of particles.

n is the dimension of particle.

c1 and c2 are the acceleration constants with positive values.

w is an inertial weight .

rand1 and rand2 are random numbers between 0 and 1.

$pbest_r$ is best previous weight of rth particle.

$gbest_n$ is best particle among all the particle in the population.

In present analysis, $\Delta K_n^{m+1} = V_{r,n}^{m+1}$, $\Delta K_n^m = V_{r,n}^m$ and $K_n^m = x_{r,n}^m$,where K are the parameters Kp, Ki and Kd of the NLNPID controller. The mean square error function is chosen as criterion for estimating the model performance as equation (21):

$$E = \frac{1}{Np} \sum_{j=1}^{Np} (T_{c,desired}(m+1)^j - T_{c,out}(m+1)^j)^2 \quad (21)$$

Np = number of samples.

The parameters values that are used in solving the PSO algorithm are shown in table (1).

5- Simulation results

The performance of the robust controller that represented in equations (15 to 18) with PSO technique is evaluated using closed loop response for the double pipe heat exchanger equations (1&2) including the changing in the physical properties in terms of the temperature and fluid velocity equation (3 to 14) with time step of 0.1 sec (total time 200 sec). The sequence of steps for present

problem solution is shown in flowchart (see figure A-1 in appendix A).

To give a more realistic for present controller, saturation limit is added to maintain the value of the hot water mass flow at logical limits. The upper limit is 5 kg/sec and lower limit is 0.1 kg/sec. The parameters of the double pipe heat exchanger that used in this simulation are given in table (2).

The values of linear PID controller has been chosen using trial and error method so that the it gives the best performance in terms of overshoot and rise time. These values are calculated at specific parameters of water as shown in table (3)

At different initial and desired temperatures of cold water the NLNPID controller is carried out and compared with PID controller as shown in figures (6, 7, and 8). It can be seen that the proposed controller able to reach the desired temperature at different working conditions without over shoot and settling time not exceed to 140 second. The responses of PID controller seem faster, but the presence of fluctuations around desired temperature and the over shoot increase when the initial and desired temperatures increase.

The flow rate of hot water (control input) responses of NLNPID and PID controllers are shown in figures (9, 10, and 11). It is clear from the figures, when using PID controller the hot water flow rate fluctuates too much inside the heat exchanger. Also the period of saturation limit increases with increase in the initial and desired temperatures as shown in figure (11). While the amount of water coming out of NLNPID controller, did not go beyond the saturation limit except at the beginning of operation.

The changing in the amount of cold water that enters to heat exchanger is important parameter that is possible affects on the performance of the of NLNPID controller. Figure (12) shows the cold water temperature response at different flow rate of cold water. It can be seen that the performance of NLNPID controller is very robust and not affected by the changes of the amount of cold water flow rate while the PID cannot give the desired temperature.

The changes in the value of nonlinear neural controller gains during the PSO algorithm solution are shown in figure (13). This solution is for case that the initial temperature of inlet water of 5 °C and desired temperature 12 °C. It is worth mentioning; that the solution of the PSO algorithm has been performed at every time step that is used to solve heat exchanger equations. Therefore; the values of PID gains are plotted against the time.

Table (1) PSO parameters

Parameter	value
c_1	1.35
c_2	1.35
w	0.73
Number of particles	3
dimension of particle (population size).	20
Maximum iteration	35
F	1.2

Table (2) Heat exchanger constant

D_i	0.0603 m
D_o	0.078 m
d_i	0.0526 m
d_o	0.0603 m
L	6 m
K_w	16 W/m ² K
\dot{m}_c	2.5 kg/sec
Re of cold water (according to the cases)	from 15000 to 26000

Table (3) linear PID parameters

Parameter	value
K_p	7
K_i	0.17
K_d	2
h_o at $T=60\text{ }^\circ\text{C}$ & $\dot{m}_h = 1$ kg/sec	3600 W/m ² K
h_i at $T=20\text{ }^\circ\text{C}$ & $\dot{m}_c = 25$ kg/sec	3100 W/m ² K
ρ	1000 kg/m ³

6-Conclusions

Three important working conditions could face controller of heat exchangers have been presented in this paper. Change in the temperature of the cold water (heated required), change in the cold water flow rate and required temperature. The proposed nonlinear neural PID controller (NLNPID) was tested at these cases. The responses of this controller have excellent features: robust, stable, smooth, without overshoot and control action (hot water flow rate) not exceeds physical limits (0.1 - 5 kg/sec) compared with the performance of traditional PID controller.

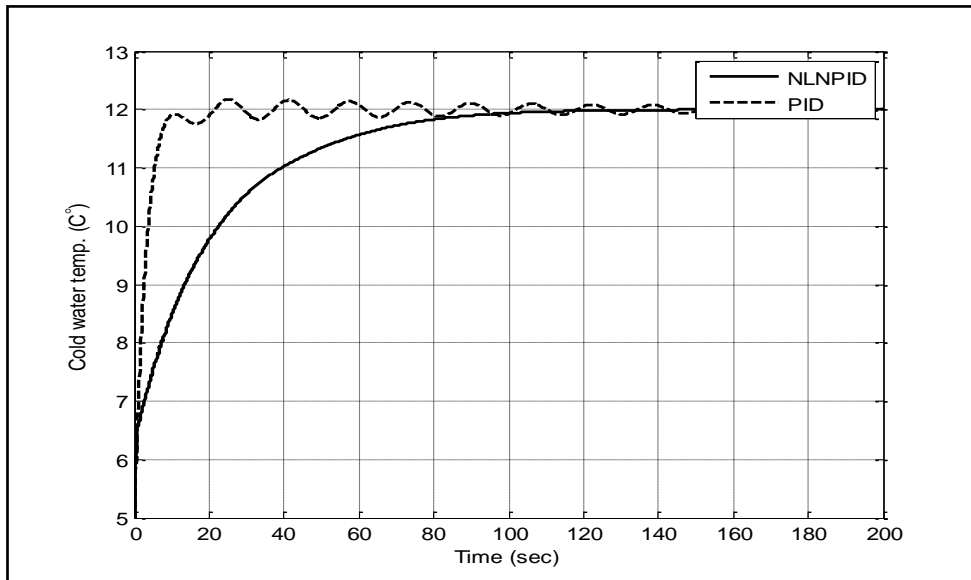


Figure (6): Cold water temperature response using NLNPID and PID controller with initial temperature 5 °C and desired temperature 12 °C

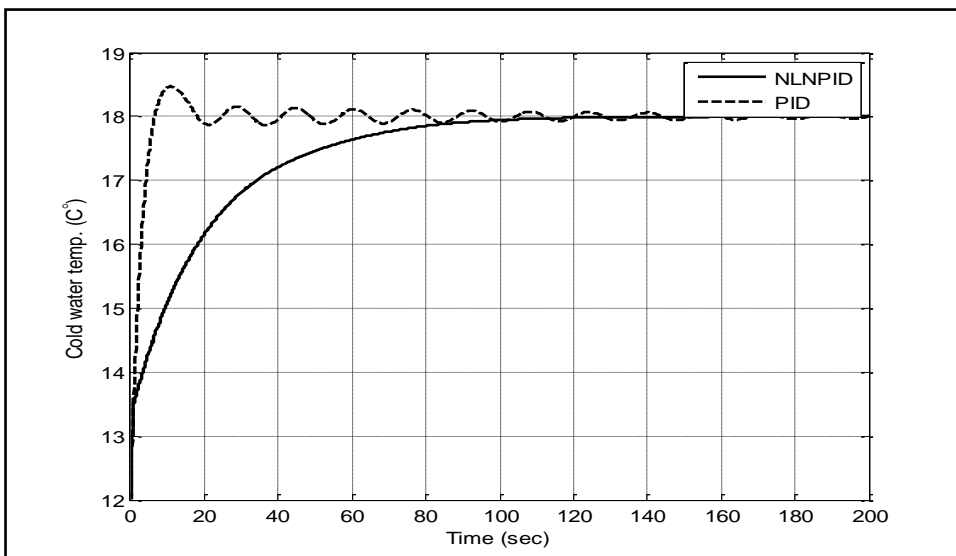


Figure (7): Cold water temperature response using NLNPID and PID Controller with initial temperature 12 °C and desired temperature 18 °C

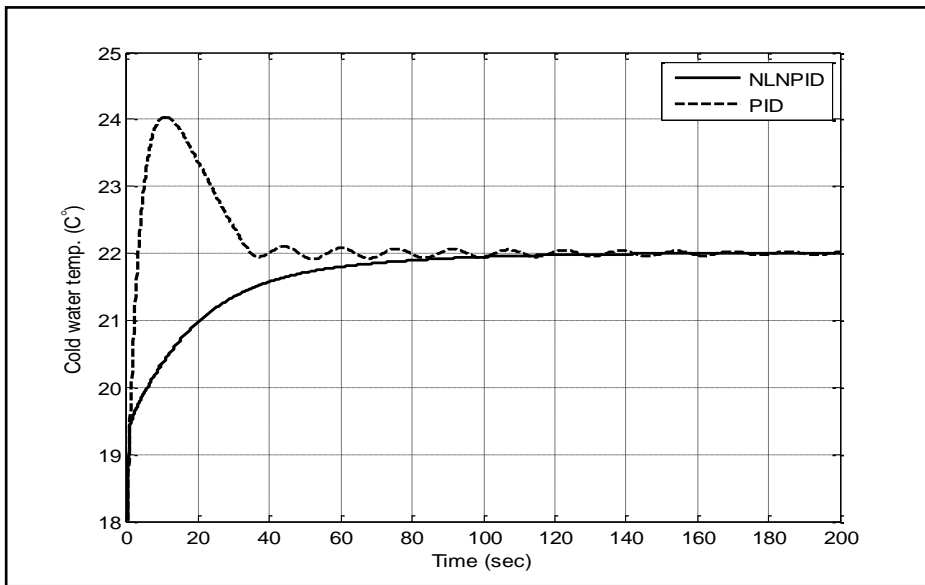


Figure (8): Cold water temperature response using NLNPID and PID controller with initial temperature 22 °C and desired temperature 26 °C

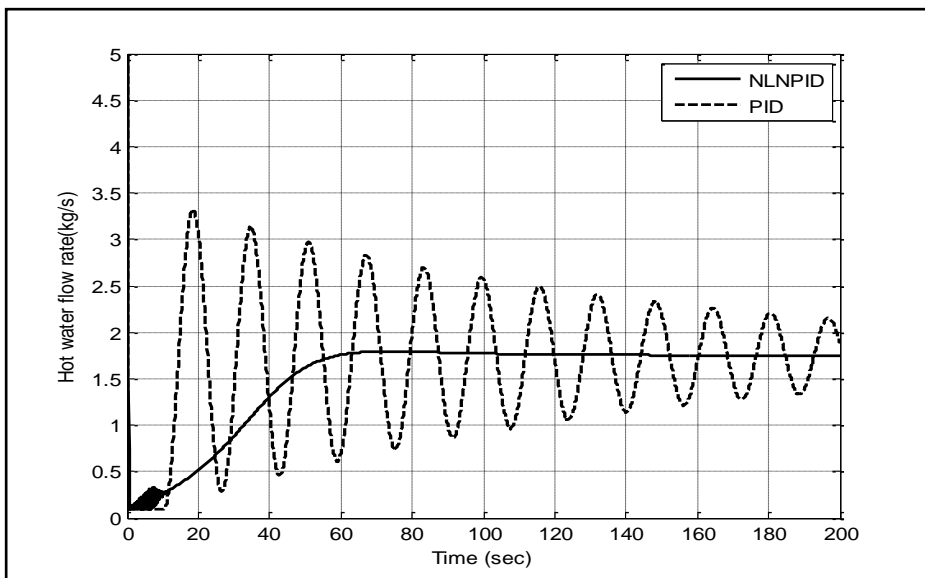


Figure (9): Hot water flow rate response using NLNPID and PID Controller with initial temperature 5 °C and desired temperature 12 °C

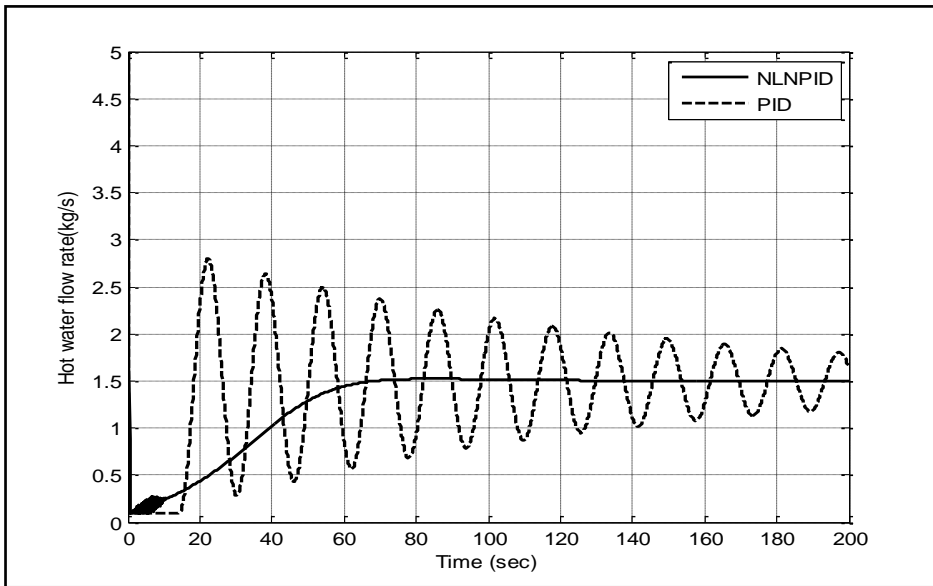


Figure (10): Hot water flow rate response using NLNPID and PID controller with initial temperature 12 °C and desired temperature 18 °C

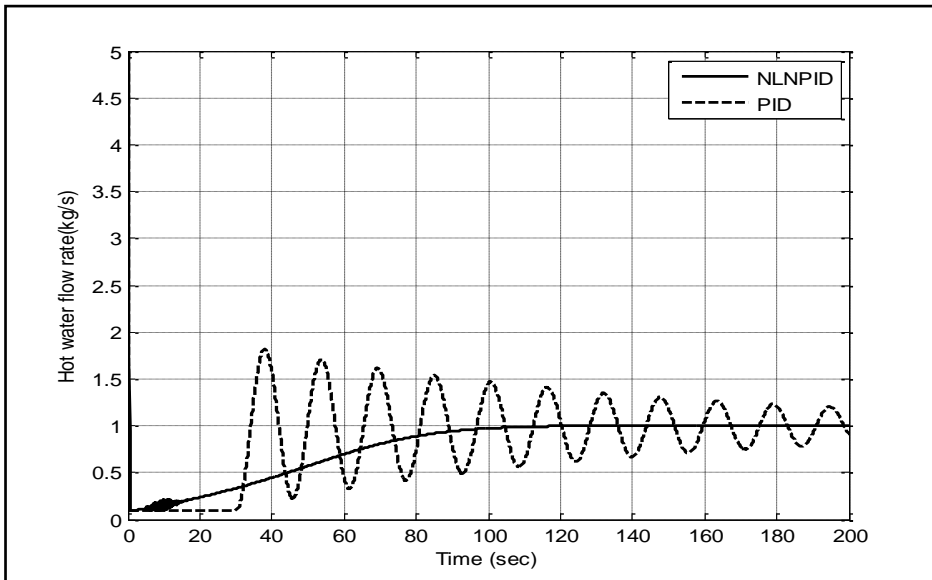


Figure (11): Hot water flow rate response using NLNPID and PID controller with initial temperature 22 °C and desired temperature 26 °C

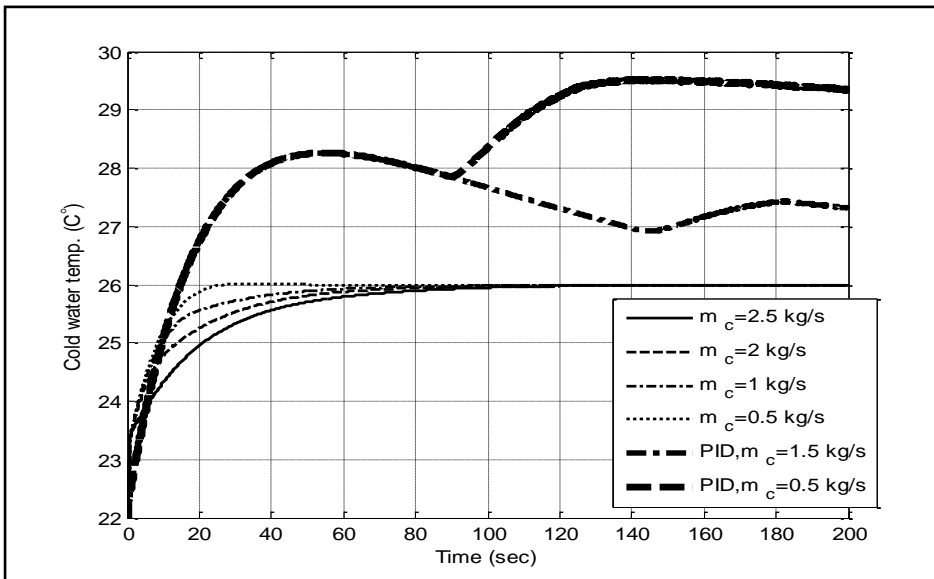


Figure (12) Cold t water temperature response using NLNPID and PID Controller with initial temperature 22 °C and desired temperature 26 °C at different cold water flow rate

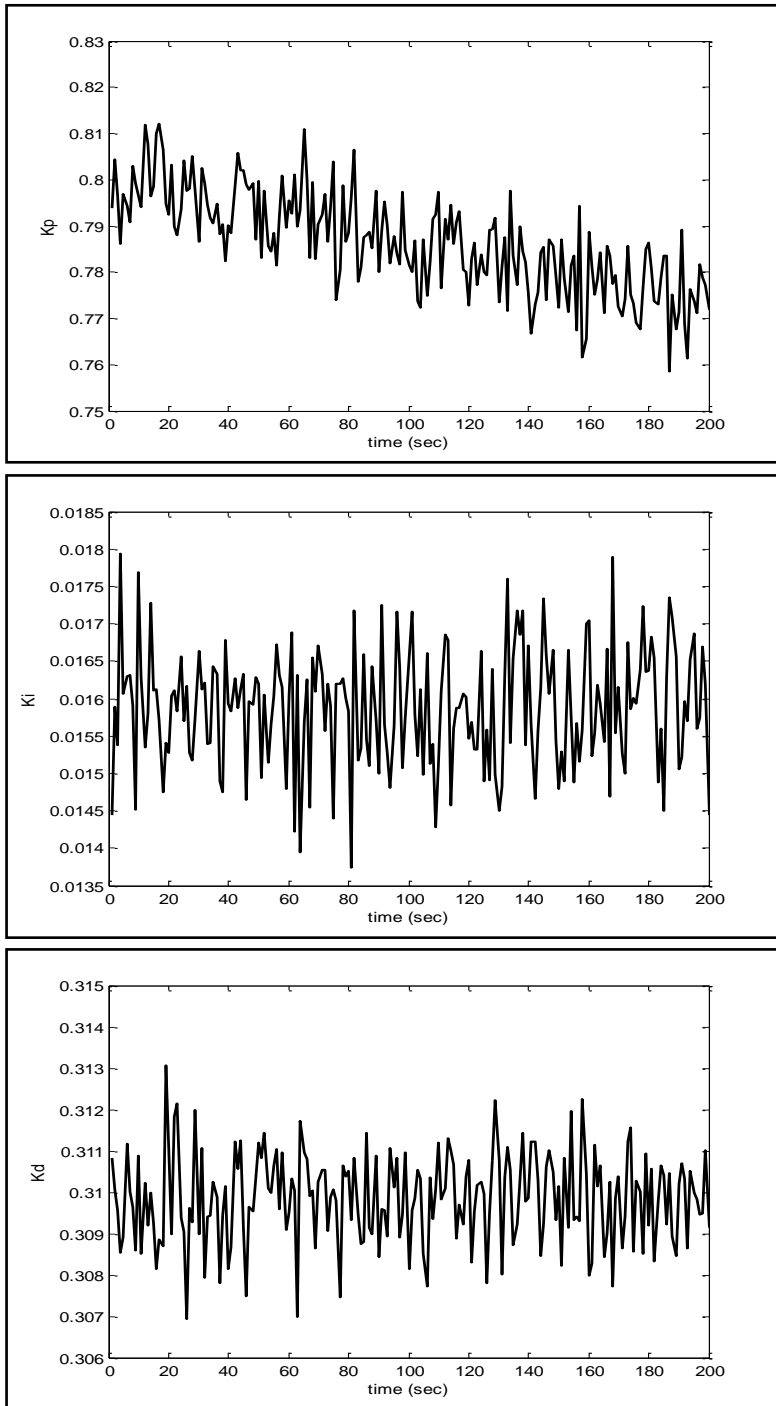


Figure (13): On line auto tuning controller gains K_p , K_i and K_d

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Appendix A

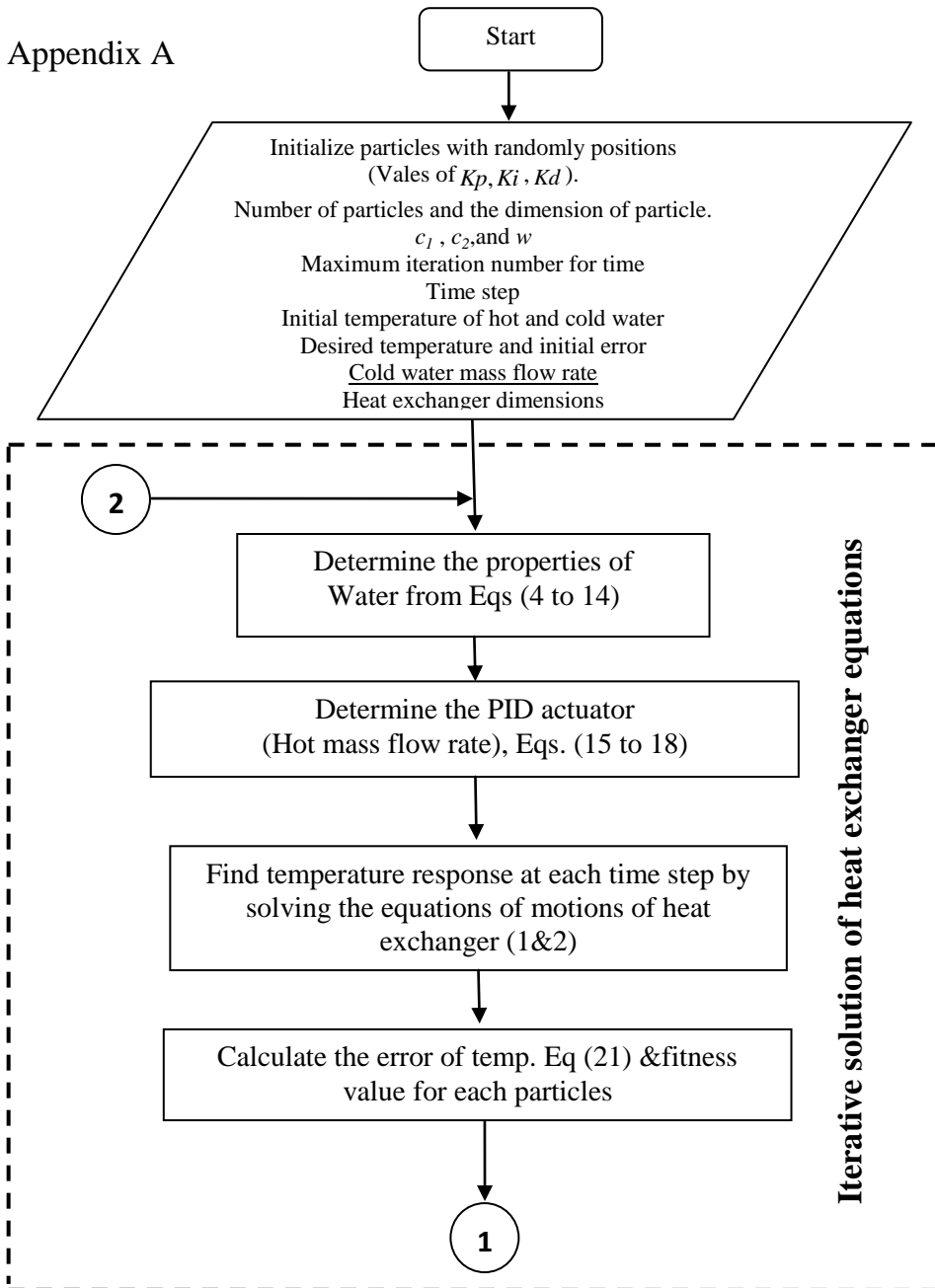


Figure (A1) Flowchart solution of Particle swarm optimization algorithm

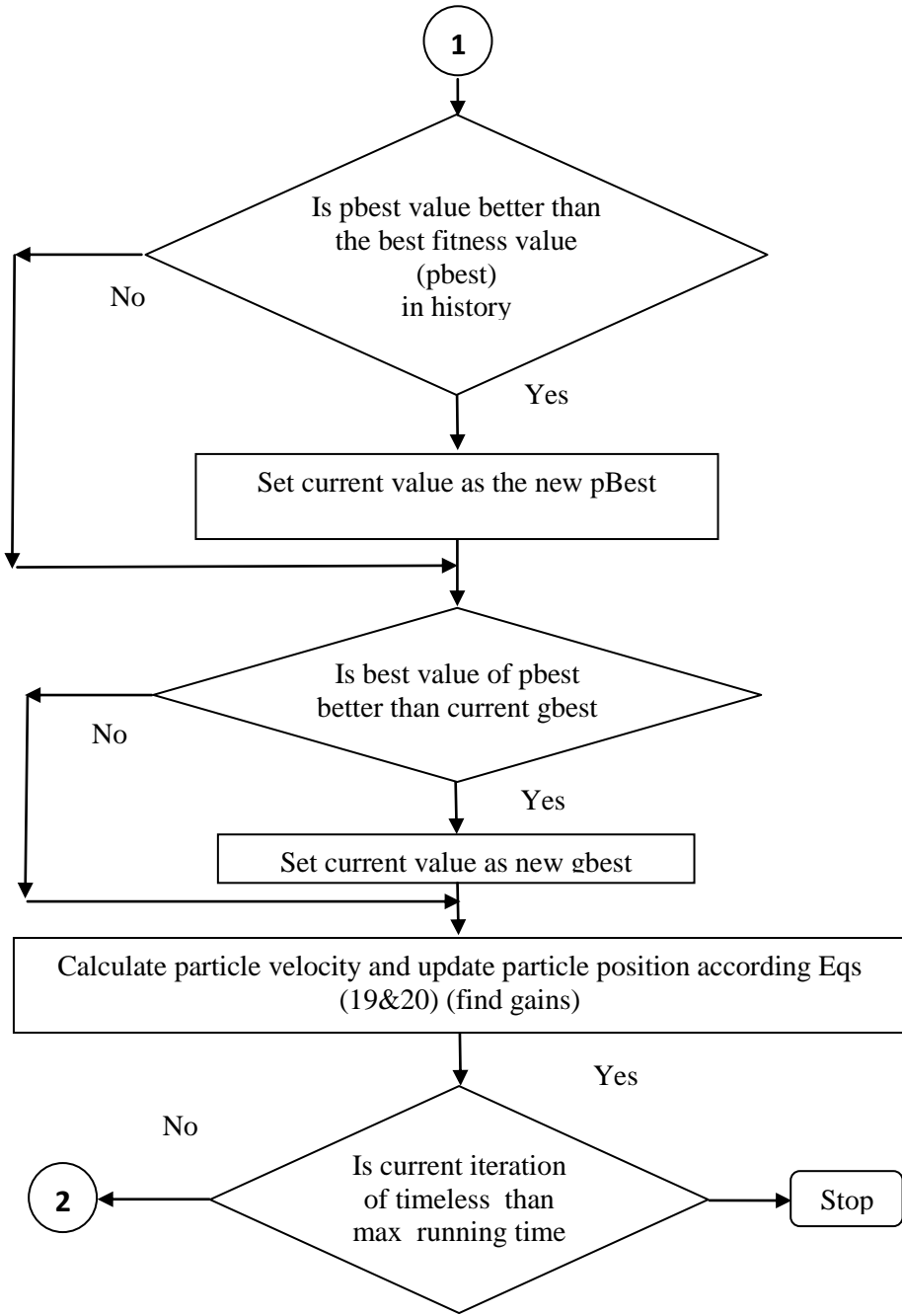


Figure (A1) cont.

Appendix B Nomenclature

A_i Inner surface area of pipe (m^2)	Ki Integral gain
A_o Outer surface area of pipe (m^2)	Kd Derivative gain
c Specific heat (J/kgK) C Heat capacity (J/K)	k_w Thermal conductivity of pipe material (W/m K)
d_i Inner diameter of inner pipe (m)	m index of time
d_o Outer diameter of inner pipe (m) D hydraulic diameter (m)	\dot{m} Water mass flow rate (kg/sec)
D_i Inner diameter of outer pipe (m)	Nu Nusselt number
D_o Outer diameter of outer pipe (m)	R Thermal resistance ($^{\circ}C/W$)
h Convection heat transfer coefficient ($W/m^2 K$)	Re Reynolds number T_i Initial Temperature ($^{\circ}C$)
L Pipe length (m)	Pr Prantal number
k Water thermal conductivity (W/m K) Kp Proportional gain	

Subscript	Greek symbols
c Cold water	ρ Water density (kg/m^3)
h Hot water	μ Water viscosity (pa sec)
i inner	μ_s Water viscosity at surface (pa sec)
o outer	

تصميم مسيطر عصبي تناسبي تكاملي تفاضلي لاخطي نشيط ذاتي التنغيم وبشكل حي وامتصل لمبادل حراري مزدوج الانبوب مبني على اساس خوارزمية حشد الجسيمات

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قسم المكائن والمعدات

المستخلص

بارامترات المبادلات الحرارية تتغير باستمرار اثناء عملها. بالاضافة الى وجود العلاقات اللاخطية بين متغيرات المبادلات الحرارية. لذلك فان هذه المبادلات تحتاج الى مسيطرات لاخطية نشيطة تعطي درجة الحرارة الخارجة المطلوبة عند كل ظروف العمل. في هذا البحث تم تقديم مسيطر لاخطي نشيط للسيطرة على درجة حرارة المبادل الحراري من نوع مزدوج الانبوب. استخدمت تقنية أمثلية حشد الجسيمات لحساب البارامترات المثالية للمسيطر التناسبي التكاملي التفاضلي. النموذج الرياضي للمبادل الحراري اخذ بنظر الاعتبار التغيرات الحاصلة في الكثافة والموصلية الحرارية واللزوجة والحرارة النوعية ومعامل انتقال الحرارة بالحمل للمائع الناتجة من تغير درجات الحرارة وسرع المائع. السيطرة على درجة حرارة المبادل الحراري باستخدام المسيطر العصبي التناسبي التكاملي التفاضلي اللاخطي النشط قورنت مع السيطرة باستخدام المسيطر التناسبي التكاملي التفاضلي التقليدي. نتائج المحاكاة اظهرت ان اداء المسيطر أمثلية حشد الجسيمات انتج صفات استجابة جيدة واعطى درجة الحرارة الخارجة المطلوبة عند كل ظروف العمل بدون تجاوز الهدف والتذبذب.

الكلمات الرئيسية: المبادلات الحرارية، المسيطرات اللاخطية، PID، PSO .