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Research Article

Design of Optimal Fuzzy Controller for Heat Exchanger Temperature

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Abstract

The heat exchanger system (HES) is widely used in petroleum industries as well as in chemical applications because it may maintain the process of controlling the pressure or temperature of a liquid. In addition, HES is often complicated, and expensive devices. The heat exchanger types used in simpler applications are inexpensive but nonlinear, and their dynamic response is very weak; Therefore, it is quite difficult to be modelled, and their dynamics operation is hard to control. In this work, several methods are applied to the heat exchanger model and its control to select the appropriate model and control unit in complex working conditions. The problems that affect the dynamic parameter setting adopted by the traditional incremental proportional integrated derivative (PID) and the intelligently designed control systems which combine a fuzzy controller that adapts to a PID controller that has a better performance are studied. The traditional PID controller is always built using MATLAB-Simulink, and two fuzzy logic controllers are designed. One of the designs is based on the sine-cosine algorithm (SCA), and another uses particle swarm optimization (PSO). Results show that the sine-cosine algorithm (FLC_SCA) controller has excellent response and strength compared to PID and particle swarm dependent optimisation (FLC_PSO) is suitable for complex time-delay systems.

Keywords: fuzzy logic controller FLC, heat exchanger system HES, particle swarm optimization PSO, **s**ine-cosine algorithm SCA.

1. Introduction

Many chemical procedures encompass the production or interest of energy plain in the form of heat. The heat exchanger affects a chemical procedure to obtain a specific heat after it is cooling fluid from a high temperature and vice versa via a solid wall. In practice, these applications have diverse types of heat exchanger systems (HES), and most of them use a shell-tube system in industrial applications, as shown in Fig. 1. Shell and tube heat exchangers are possibly the highest mutual type of HTS applicable for a wide temperature range in operating pressures. In the shell and tube of the HES, the first fluid flows through the tubes, and the second fluid flows within the space between the tubes and the shell,[1]. The outlet temperature of the shell and tube of the HTS should save the desired set point regarding that procedure's condition. Fig. 1 shows the schematic illustration of the heat exchanger. The complicated design of the HES actuators of the controller and its sensors feedback has a limitation represented in a more serious problem to obtain the point of optimal energy depletion. The problem lies in the nonlinearity of the system behaviour. The objective of this paper to design a real temperature plant that consists of a plate HES, a reservoir through the heated liquid, two thermocouples, and a motor-driven valve. The plate of HES, over burning water using an electrically heated, is unceasingly circulated by the current flow to the cold process fluid, [2]. The thermocouple T/C is positioned into the inlet and outlet flows of the heat exchanger, and then the flow rates can be monitored. Controlling the flow of the heated fluid is a function of the proportional motor-driven valve, and the external control loop can be used to govern the power of the heater to control the proportioning of time.

Fuzzy logic addresses that a fuzzy logic controller (FLC) can solve many complex applications and non-linear systems, because it perfectly simulates the human decision-makers' aptitude to generate precise resolutions, [3]. However, the drawback of this controller is the difficulty in determining the parameters of FLC. A classical FLC is implemented using trial and error, and this controller may exhibit undesirable high overshoots during settling time, [4].

The Particle swarm optimization (PSO) algorithm can be used to obtain an optimal FLC, [5]. It is a powerful method to tune the parameters of FLC to minimise the overshoot and reduce the settling time.

In this study, two models are considered for the design of smart control systems to achieve a high-efficiency heat exchanger. The latter that carries the specifications of the most complex devices despite the simplicity of the system. In addition, it has an efficient control design and a low cost compared with required expensive devices. The first model considers a design of an obscure logic control system, which use the sine-cosine algorithm (SCA). The second control model considers the design of a fuzzy logic type, which is based on the use of PSO - based algorithm.

This study is organized as follows: Section 2 briefly introduces the HES and describes assumptions made and sources of disturbances along with the mathematical modeling of the system. Section 3 describes the FLC and its tuning, membership function, and rule base. Section 4 describes the PSO. Section 5 shows the simulation model and its resultant graphs. Section 6 presents the results, discussions, and conclusion.

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2.Heat Exchanger Model

2.2 Heat exchanger definition

For the purpose of constructing a controller, the hierarchy of the work of the heat exchanger must first be clarified, as shown in Fig. 1. The process begins with the flow of fluids into the heat exchanger by means of pumps. Thermo sensors are used to determine the temperature of liquids at the outlet of the exchanger. The heat exchanger feed rate is controlled using a fail-close type valve due to the reverse acting characteristic of the feedback controller.

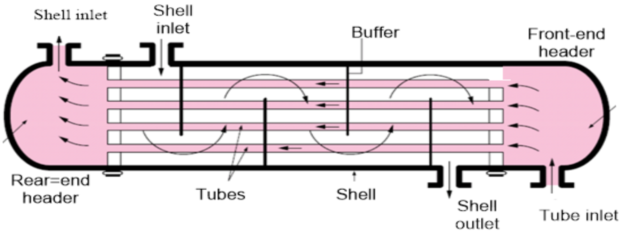

Fig. 1. Work of the heat exchanger.

2.2 Heat exchanger design

The HES transports heat between different fluid streams. One of them has high temperatures and phases, and the other works at low temperatures. This interaction is obtained without mixing them. They are classified into two types according to the contact (direct and indirect) and media are disconnected via the solid wall. Direct contact HES can achieve closer temperatures because of the absence of a wall, and heat is repeatedly motivated by mass transfer. Indirect-contact in HES is determined by the plate wall that separates streams of (hot and cold) liquids, and heat flows between them through this interface, [6] mentioned the examples of plate and tube HTSs that produce an indirect contact.

The amount of heat that is not bound by the hot liquid (Q_h), and the heat that is absorbed by the cold liquid (Q_c) should be calculated to determine the heat performance of the HES. In addition, the amount of heat lost from the exchanger to the surrounding atmosphere can be determined.

$$Q_h = \dot{m}_h c_{ph}(T_{hi} - T_{ho}) \tag{1}$$

$$Q_c = \dot{m}_c c_{pc}(T_{ci} - T_{co}) \tag{2}$$

where the kinetic energy and potential variations are neglected, Shah [7]. According to the law of heat protection, $Q_c = Q_h = Q$ is the rate of the energy and Q is dependent on coefficient U which represents the total energy transfer, and LMTD refers to the mean temperature difference, Chen et al [8]:

$$Q_c = U\,A\,LMTD\,C_f \tag{3}$$

Where

$$LMTD = \frac{\Delta t_1 - \Delta t_2}{\ln\left(\frac{\Delta t_1}{\Delta t_2}\right)} \tag{4}$$

$$\Delta t_1 = T_{ho} - T_{ci} \tag{5}$$

$$\Delta t_2 = T_{hi} - T_{co} \tag{6}$$

where A represents the entire surface area of heat exchange, and Cf is the correction factor. The heat exchanger was developed and designed in several simplified ways to solve many problems. One of the most prominent of these methods is the Epsilon-NTU heat exchanger analysis method. In this method, the efficiency of the heat exchanger (ε) is defined as the percentage of the actual heat transfer rates for a given moment to the maximum rate that the heat transfer can reach. This case only applies if the surface area is unlimited. Eq. 8 depends on whether the flow rate of the hot liquid or the cold liquid is the minimum fluid quantity, Thulukkanam [9]:

$$\varepsilon = \frac{c_{max}\,(T_{hi} - T_{ho})}{c_{min}\,(T_{hi} - T_{ci})} \tag{8}$$

Otherwise, when the hot liquid possesses a minimum amount of fluid, then the effectiveness is defined as:

$$\varepsilon = \frac{c_{max}\,(T_{co} - T_{ci})}{c_{min}\,(T_{hi} - T_{ci})} \tag{9}$$

The rate of HTS can be written as:

$$Q = \varepsilon\, C_{min}\,(T_{hi} - T_{ci}) \tag{10}$$

The NTU is defined as the ratio between UA and the minimum amount capacity of fluid and can be expressed as:

$$NTU = \frac{U\,A}{C_{min}} \tag{11}$$

$$C_r = \frac{C_{min}}{C_{max}} \tag{12}$$

The epsilon, ε, NTU relationship is a simple heat exchanger because it consists of double counter-flow tubes with a small C_r.

$$\varepsilon = \frac{1 - \exp[-NTU(1 - C_r)]}{1 - C_r \exp[-NTU(1 - C_r)]}, \quad C_r < 1 \tag{13}$$

In the next section, the two assumptions for designing smart control systems are explained. First, the model is a fuzzy logical type control system, and its design is based on SCA. The second model of control consists of a fuzzy logical type, and; its design is based on the use of an algorithm based on PSO.

3. Control Algorithms

3.1 Fuzzy Logic Controller

The components intelligent temperature control system for the HTS is shown in Fig. 2. The most appropriate application of fuzzy control is to meet the specific requirements of satisfactory control procedure. The fuzzy logical rules are identified in, Duch et al [10]. Table 1 illustrates the rules of FLC. The latter has proven its ability to deal with complex, indeterminate, nonlinear, or changing systems over time, Hettiarachchi et al [11]. Thus, the rule-based control model often produces better controls than those based on the analytical control theory model. Fuzzy logic is one of the most rapidly developing control systems over time due to its ease of use. Fig. 2 presents the block diagram of the FLC design implemented using MATLAB/SIMULINK. Error signal, u, is the difference between desired temperature fluid and outlet temperature. The FLC should be designed with two inputs variable and one output variable. The error signal and its deferential are used as the two input signals to the FLC system.

Table 1. Rule of the FLC

Error signal u/ du/dt	**Negative N**	**Zero Z**	**Positive P**
Negative N	More Negative MN	Negative N	Zero Z
Zero Z	Negative N	Zero Z	Positive P
Positive P	Zero Z	Positive P	More Positive MP

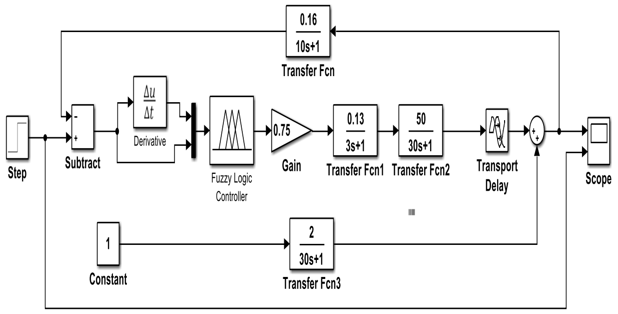

Fig. 2. Block diagram unit design with FLC using MATLAB/SIMULINK

3.2 PID controller

Generally, the PID controller is not a powerful method similar to the FLC that can minimize the overshoot and reduce the settling time. However, tuning PID is very simple today and has become one of the greatest methods that can develop the parameter of PID controller using MATLAB/SIMULINK. The block diagram unit design PID controller is presented in Fig. 3.

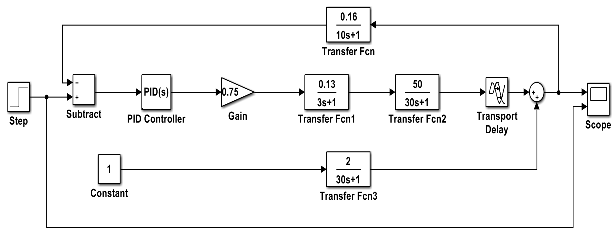

Fig. 3. Block diagram unit design with PID using MATLAB/SIMULINK

4. Optimization Algorithm and Methodology

4.1 Particle Swarm Improvement

PSO is a computational algorithm and has been introduced as a powerful tool in the solution. It was first proposed in 1995 by researchers Eberhart and Kennedy, Imran et al [12]. Many nonlinear or non-differential problems need to be solved using effective methods. This method can provide powerful solutions. This method is inspired by nature and mathematical equations simulating the life of several animals. It affects groups of fish or flocks of birds in their behavior whilst foraging for food. The gene algorithm (GA) mimics the evolutionary theory and transforms gene junction during mating while, PSO does not need such procedure. PSO is an idea based on a random sampling of particles sharing experiences to come up with the best solution. Presumably, these elements fly in several directions to find a better fitness job, Blackwell et al [13]. This method has n-dimensional directions to illustrate the problem space. Eq. 14 explains the particle kth with a space of dimensions n and Eq. 15 forms the best position in it.

$$x_{\_k} = \left(x_{\_k,1}, x_{\_k,2}, x_{\_k.3} \dots\dots x_{\_k,n}\right) \quad (14)$$

$$P_{\_best\,k} = \left(P_{\_best\_\,k,1}, \; P_{\_best\_\,k,2}, P_{\_best\_\,k,3} \dots\dots P_{\_best\_\,k,n}\right) \quad (15)$$

Several researchers consider the velocity equation as an essential part of how the PSO works, Chander et al [14] and can be calculated using Eq. 16. This equation clarifies that adjusted speed depends on numbers that the calculator selects randomly and the distance between ($P\_{\,best\_\,(k,\,d))}$) and ($g\_{\,(best\_d)}$). The current velocity can adjust the position of each particle using Eq. 17.

$$V^{(Iter.+1)}_{\_k,,m} = W * V^{(Iter.)}_{\_k,m} + c_1 * r * \left(P_{\_best\_k,m} - x^{(Iter.)}_{\_k,m}\right) + c_2 * r * \left(g_{\_best\,m} - x^{(Iter.)}_{\_k,m}\right) \quad (16)$$

$$x^{(Iter.+1)}_{\_k,m} = x^{(Iter.)}_{\_k,m} + v^{(Iter.)}_{\_k,m} \quad (17)$$

where k= {.1, .2, .3 …., is the number of particles, m= {.1, .2, .3 …} is the space of dimensions, {Iter.} is the iterations of the pointer in Eqs. 16 and, 17, C_1 and C_2 are acceleration constants, r_1 and r_2 are arbitrary random variables whose values are taken from (0) to (1), w is a factor referring to (inertia weight).The kth particle at iteration (*Iter.*) has a velocity ($V_{k,m}^{Iert}$) and position ($X_{k,m}^{Iter}$). The previous best position of the kth particle is ($P\_{best.}$). All the swarms have only one (G_{best}), and it is named the global best position that refers to desired solution.

4.2 Sine- Cosine Algorithm

The Sine- Cosine Algorithm (SCA) is an innovative population-based optimization algorithm proposed for solving optimization problems. It was first proposed by Seyedali Mirjalili in 2017 [15]. The SCA generates many initial random contestant resolutions and their requirements to fluctuate towards or out of the preeminent solution. The mathematical model of SCA is based on sine and cosine functions. The SCA has many random variables that are integrated to emphasize exploitation and explore the optimization search in different spaces, as shown in Figs. 4 and 5.

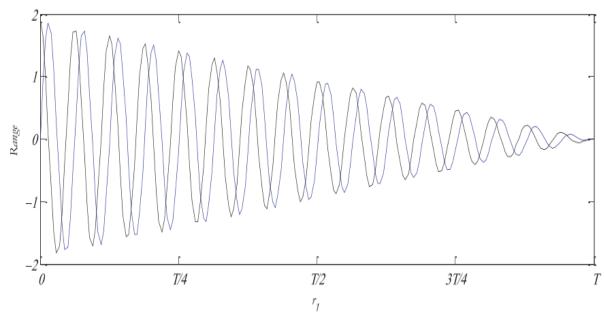

Fig. 4. Definition of how sine- and cosine can be reduced to reach the optimal solution

```
Initialize a set of search agents (solutions)(X)
Do
   Evaluate each of the search agents by the objective function
   Update the best solution obtained so far (P=X*)
   Update r1, r2, r3, and r4
   Update the position of search agents
While(t< maximum number of iterations)
Return the best solution obtained so far as the global optimum
```

Fig. 5. SCA algorithm

4.2 Tuning FLC based on PSO and, SCA

The controller can be realized by closed-loop control. In our work the outlet temperature of the HTS HES should be governed. In the same procedure, two diverse methods, namely, PSO and SCA, are used to design the FLC by finding the parameters of memberships and their shapes in FLC. The control algorithm is considered to achieve the desired control objective and another one using the control module. The control problem is also the decision problem, that can be observed from the process case to determine the action taken from the coding knowledge. Knowledge-based systems, especially rule-based approaches are ideally suited for this decision-making task. The fuzzy controller is a simple rule-based control strategy. All applications of FLC are recognized as fuzzy logical rules similar to Table1. Thus, a rule-based control model often results in better controls than an analytical control theory model. The two algorithms PSO and SCA are used to design the shapes of memberships of Mamdani FLC. The block diagram of a closed-loop feedback control setup of the HES is shown in Fig. 4. In this figure, it can be noted that the SCA-based smart control system considers a scheme which is similar to the one in PSO. The heat exchanger real-time FLC is designed on a laboratory scale using the Mamdani method. In this work, the tuning is divided into two parts. In the first part, the algorithm tunes the optimal widths for the two inputs, and the output of the second tuning is to find the optimal triangle shapes for each membership. The effectiveness of the proposed controller over FLC-SCA is further viewed in terms of reducing the integral of summation error (ISE). Error-value ISE is the fitness function of the SCA and PSO.

5. Simulation Results

Industrial control device performance evaluation is a widely researched area that defines controller performance in various ways. The effectiveness of the designed FLC, FLC-SCA, FLC-PSO, and PID controller is tested in real-time using MATLAB simulator. Fig.6 shows the comparison between FLC and PID controller. Fig.7 shows the shapes of memberships designed by PSO. Fig.8 shows the shapes of memberships designed by SCA. With the step function, Fig.9 shows the time response of three controllers. Fig.10 shows the step response of optimal (FLC-SCA) and FLC before tuning the memberships. Fig.11 shows the step response of optimal (FLC-SCA) and it's FLC before tuning the width of memberships. Fig.12 shows the step response of the PID controller with the optimal PID controller after tuning. That can be summarized as table-2 in this table the FLC-SCA gives a supreme performance than other controllers. Where, the criteria of the optimization (integral of summation error (ISE) finesses function) was 2.98, but the other controller FLC-PSO gave 3.27. Also the maximum peek overshot in proposed controller was very small it didn't exceed 0.5%. In FLC-SCA the controller has relatively large rise time. But, its settling time is the best it's about 17.6 sec.

Table 2. The Time-Response of deferent controllers are used

Controller	Rice time (sec)	Maximum pick overshoot	Settling time (sec)	Optimization criteria (ISE)
PID	11.2	21%	77.3	5.12
Tuned PID-SCA	11.2	10%	51.1	4.78
FLC-PSO	8.5	2%	21.4	3.27
FLC-SCA	15.2	0.5%	17.8	2.98

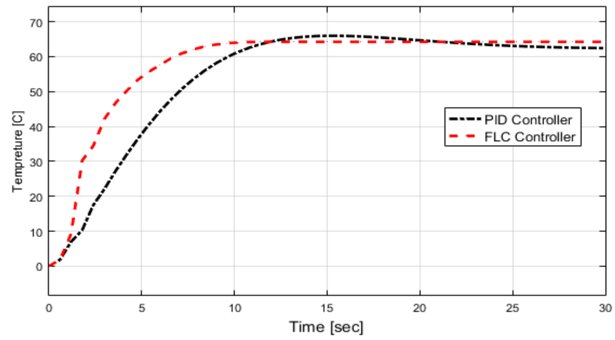

Fig. 6. Step response of PID and FLC

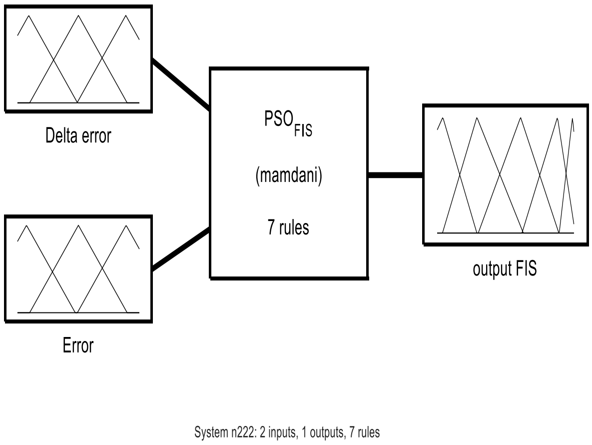

Fig. 7. FLC tuning memberships using PSO

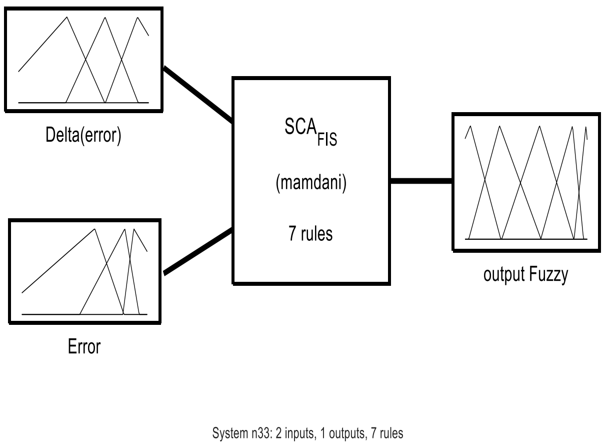

Fig. 8. FLC after tuning the member ships functions using SCA

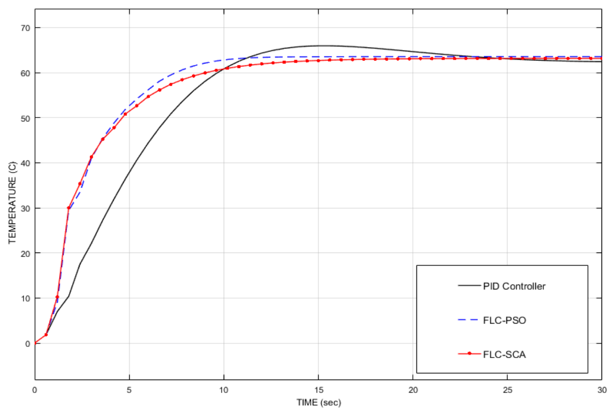

Fig. 9. Step response of the optimal FLC with optimal PID

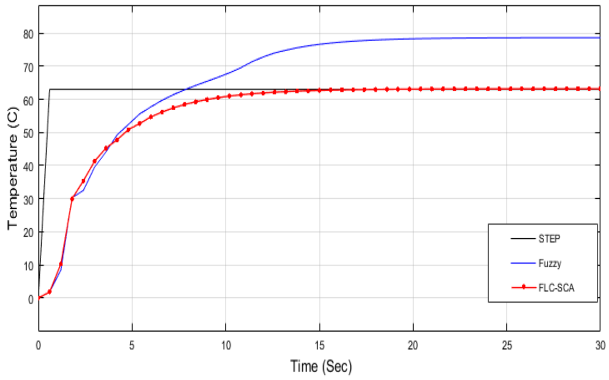

Fig.10. Step response of optimal (FLC-SCA) and FLC before tuning the memberships

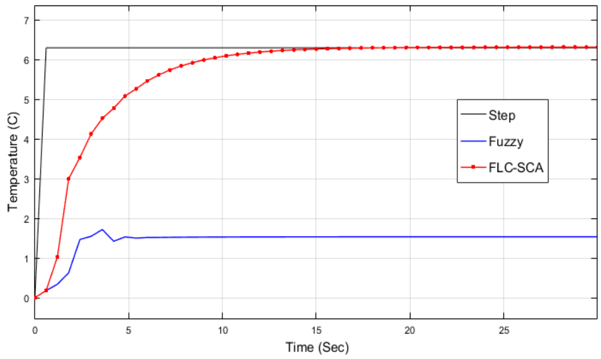

Fig.11. Step response of optimal (FLC-SCA) and FLC before tuning the width of memberships

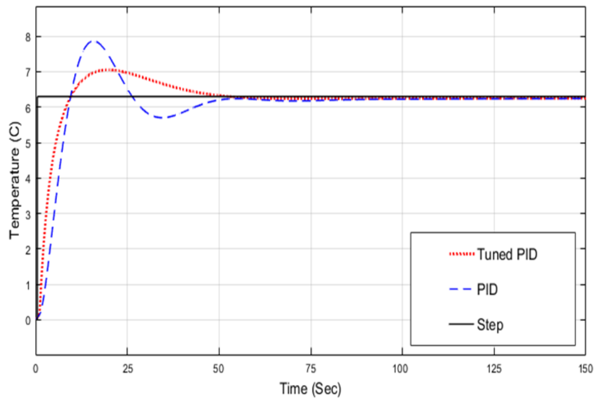

Fig. 12. Step response of PID controller with optimal PID controller after tuning

7. Conclusion

Figs.7 and, 8 demonstrate that using the computational algorithms is a supreme method in designing of the FLC without any cumbersome process or trial and error. Fig. 9 shows, that the FLC-SCA controller tracks the set-point effectively and in less time compared with the FLC and PID control systems. The PID unit displays poor performance because it takes a scattered path to reach a set-point. Nevertheless, the system has many inherent advantages because the system HES is governed by FLC-SCA and controller FLC-PSO over the other controllers. The current to pressure (I/P) converter alters the position of the control valve, thus changing the flow rate of the cold water. The proposed system has an intelligent temperature control system for the heat exchanger. This intelligence is the outcome of the prediction in fuzzy logic control.

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