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Fuzzy and ANN Controller for Stable Temperature of Liquid in Heat Exchanger

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Abstract: Heat exchangers are an essential ingredient in a wide range of industrial applications. During the heat exchanger process, the temperature of the liquid changes in different ranges. Controlling the temperature changing range and achieving the desired temperature is a difficult process. Various controlling techniques are used to control the temperature changes of liquid heating system. In this paper, Neural Network (NN) based controller and Fuzzy Logic Controller (FLC) is used to achieve the desired liquid temperature. Initially, the error temperature and change of error temperature of a liquid heating system is determined. Then, the temperature variation is applied separately to FLC and NN-based controller. Then based on the controller output, the Automatic Control Valve (ACV) is adjusted till the desired temperature is reached. The proposed system is tested in real time environment and the output performances are evaluated.

Keywords: Water Heating System, Heat Exchanger, Fuzzy Logic Controller, NN Controller (NFC), Desire Temperature.

I INTRODUCTION

To control the various system processes is the main issue that arises in the process industry. It is very important to keep the process with working probably and safely in the industry, for different environmental related issues and for the quality of the product being processed [2]. To control quality characteristics on the methods, machine, products, equipment's both for the company and use by operators, the Statistical Process Control (SPC), Statistical Quality Control (SQC), and Quality Improvement methods are widely recognized as an effective approach to process monitor and diagnosis [3]. Intelligent systems cover a wide range of technologies which are related to hard sciences, such as modeling and control theory, and soft sciences, such as the artificial intelligence (AI) [1]. An Engineering Process Control (EPC) strategy is used to improve quality that have been developed independently [5].

Statistical methods play an important role in the quality improvement process in different manufacturing and service industries. Statistical process control, a sub-area of SQC, consists of different methods to understand, monitor, and to improve process performance over time [4]. Proportional Integral Derivative (PID) controllers are the best industrial process controllers and are widely form of feedback in use today [7] [9]. This is due to the process input which is controller output and the process output which provides new equilibrium values before error goes down to zero [6]. PID controllers perform well for a different class of processes and they provide strong performance in a wide range of operating conditions [12]. The conventional PID controller is not suitable for nonlinear systems [8]. The combined effect of feedback and feed forward control schemes provides a much better result than the feedback PID controller [11] [13].

PID controller in the first-order process provides a short-term regulation, such as fuzzy PID controller [10]. Fuzzy Logic Controller (FLC) is developed to provide an intelligent control in mechanical systems [18]. Fuzzy logic attempts systematically and mathematically to simulate human reasoning and decision making. It also provides an intuitive way to implement control systems, decision making and diagnostic systems in various branches of modern industry [15]. In most cases, an Artificial Neural Network (ANN) is an adaptive system that changes its structure which is based on external or internal information that flows through the network during the learning phase [19]. Design of a Neuro-Fuzzy Controller (NFC) is also considered because of their insensitivity to disturbance and uncertainty of model parameters [17]. The concepts of FLC and ANN for control problem are developed to control the inaccuracy of mathematical model of the plants usually it degrades the performance of the controller, especially for nonlinear and complex control problems [14] [16].
Generally, the water heating system is functioned based on the heat exchanger operation for changing the temperature

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of water form one level to other level. During the temperature changing process, the controller is used for achieving the desired temperature. More controllers are used in the literature for maintaining the water heating system. In this paper, NFC based controller is proposed for achieving the desired temperature.

II. RELATED WORK: A BRIEF REVIEW

Numerous researches related works are available in the literature which is based on process controller. Some of them are reviewed here. Nandwana*et al*. [20] have proposed that Fuzzy logic is suitable for complex, ill-defined, nonlinear processes where human experience has an edge over mathematical tools. Thus, the application of the fuzzy logic can improve the wire manufacturing process to make it automated and error free. One of the most preferred steps of all is to control the temperature of the poly vinyl chloride (PVC) material and it was controlled by using fuzzy logic.

Malhotra*et al*. [21] in their research have discussed that different technological innovations in soft computing techniques have brought automation capabilities to new levels of applications. Conventional control theory was based on mathematical models that described the dynamic behavior of process control systems. Fuzzy logic was a flexible approach to conventional controllers. Conventionally, the plants in an industry were controlled by PID controller with Ziegler- Nichols (Z-N) method. FLC, which were based on human knowledge, were more flexible than conventional PID controllers. Zaid Amin Abduljabar [26] has proposed a computer simulation based FLC model to control temperature of heating and cooling liquid System. For the complication of membership function range selection, the FLC does not provide smooth performance with respect to process changes.

AmitSalunkhe [22] has suggested a Multi–Fuzzy Inference System to improve the overall performance of a plant. The proposed Multi– FIS was designed for different set point to control temperature of liquid chamber. Three FIS files were designed for three different temperature set points. Here, the desired set point of the system is attained from the different kind's set point. So, the complexity and accuracy problem is occurred in the FI system.

Samikannu*et al*. [23] have suggested a NFC, which eliminates sudden input disturbance and maintain the already set temperature point in the plastic extrusion system. The experimental results have shown that NFC has reduced the different timing specifications of Fuzzy, Neural and PID controllers. They have also examined the effectiveness of intelligent controller on non-linear system particularly for temperature control in plastic extrusion system. The comparison of performance of these three controllers has shown that the NFC was superior as compared to the other controllers.

III. WATER HEATING SYSTEM

Heating water is a thermodynamic process, where an energy source is utilized to heat water above its initial temperature. The main parts of the proposed water heating system are Cold water tank, Hot water tank, Condenser, and Controlling unit. The description of the water heating system parts are described below. The structure of the proposed water heating system is illustrated in Fig.1.

A. Cold Water Tank

The cold water tank is one of the parts of water heating system, which supplies the cooling water to the condenser. It consists of float level indicator, which is used to indicate the water level of cooling water tank. The supply of cooling water is controlled by MCV1 control valve.

B. Hot Water Tank

In the proposed water heating system, the hot water tank supplies the hot water to the condenser. It contains heater circuit, stirrer and float level indicator. The heater circuit consists of Resistance Temperature Detector (RTD), ON/OFF switch and heating coils. The heater circuit will work based on the temperature changes of the hot water tank. The temperature change of the hot water system is detected by RTD. Then, based on the temperature detected value, the temperature is changed by heating circuit. The stirrer is a metal device, which is used to mix the hot water by rotating magnetic field. The hot water tank consists of two manual control valves: one is MCV2 called Automatic Control Valve (ACV), and other is MCV3 called Safety Valve (SV). The ACV and SVmaintain the heat ratio of the condenser, and they are controlled by NFC based controller output.

C. Heat Exchanger

In water heating system, the condenser is a device, used for changing the heat of the water typically by adding hot water. The condenser consists of two tubes: inner tube and outer tube. The inner tube contains cold water and the outer tube contains hot water. The inner tube water temperature is controlled by the outer tube of the system. Here, the condenser is worked based on the heat transfer principle. The exhaust hot water is removed through the MCV4 control valve. The temperature of the inner tube in the condenser is maintained by detecting the water temperature using RTD.

D. Controlling Unit

The controller is used to control and determine the water temperature ratio of the condenser. The temperature of the

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condenser inner tube is detected by RTD and the detected output is applied to the input of bridge circuit. The bridge circuit filters the temperature changes and applied to the instrument amplifier. Then, the analog input is converted to digital and applied to the NFC controller for determining the water temperature ratio. The output of NFC controller is compared with the reference pneumatic source.

The formula for flow rate (Q) and the temperature (T_c) of the condenser in the water heating system are given below,

Flow Rate, $Q = AV$ (1)

Temperature of Condenser, $T_c = \frac{k\,A(T_{hot} - T_{cold})}{d}$ (2)

where, A - area of the circular pipe i.e. $A = \frac{\pi}{4} D^2$

D - diameter of the pipe,
k - metal coefficient,
T_{hot} - outer tube temperature of the condenser,
T_{cold} - inner tube temperature of the condenser,
d - thickness of the inner tube.

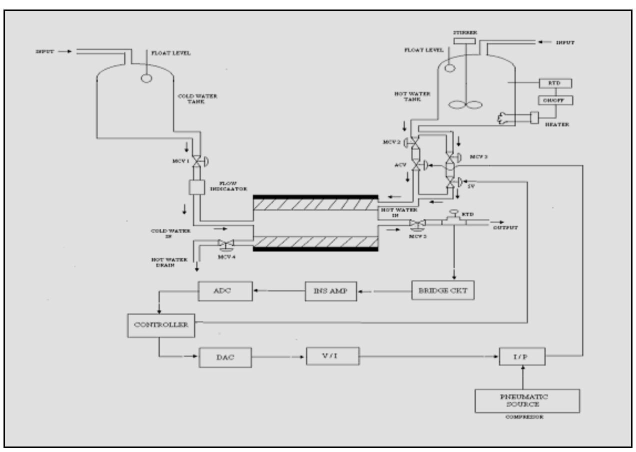

Figure 1: Structure of Proposed Water Heating System.

IV. DETERMINATION OF WATER TEMPERATURE RATIO USING FUZZY AND NEURAL NETWORK (NN)

Fuzzy Inference System (FIS) and NN is used to calculate the water temperature ratio of the water system. Here, the fuzzy controller is operated based on the fuzzy rule and NN is operated based on training dataset. From the fuzzy rules, the network training dataset are generated. The ratio of water temperature is determined from the current temperature and the change of temperature. From the value of current temperature and desired temperature the change of temperature of the water system is determined. The formula for change of temperature is described as follows,

$$Change\ of\ Temperature\,(\Delta T) = T_{desired} - T_{current} \quad (3)$$

where, $T_{desired}\ and\ T_{current}$ are the desired and current temperatures. The current temperature of the water system is calculated for different time instant and the maintained temperature is selected as the desired temperature. The prolonged utility of Fuzzy and NN is explained in the below section.

A. Determination of Water Temperature Ratio Using FLC

In control technology, FLC is one of the fastest growing controller and has better projections for the future. In feedback control system, FLC is more effective and easier to implement. The FLC is divided into two types based on the control variables: i) single variable fuzzy control system, and ii) multi-variable fuzzy control system [27]. The proposed water heating system is operated based on multi-variable fuzzy control system. The operation of fuzzy control system is mainly relies on fuzzy rules, which are generated using fuzzy set theory. The phases of fuzzy control system are fuzzification, decision making and defuzzification. The fuzzified error temperature and change of error temperature are applied to the decision making process, which contains a set of rules. Then, the defuzzification process is applied and the water temperature ratio is determined. The steps for designing FLC are pointed below and the structure of designed FLC

- ➢ Select the control variable of the water temperature ratio.
- ➢ Determine the error temperature 'e'and change of error temperature 'Δe'value of the system.
- ➢ Set the fuzzification process.
- ➢ Design the decision making rules.
- ➢ Set the defuzzification process.
- ➢ Test the output of the water system.

The inputs of FLC are e and Δe, and the output is T_R^F. The linguistic variables of $e,\ \Delta e\ and\ T_R^F$ are Very Big Negative, Negative Big, Negative Medium, Negative Small, Zero, Positive Small, Positive Medium, Positive Big, Very Big Positive and it is referred as VBN, NB, NM, NS, ZE, PS, PM, PB, VBP in the rules base. The developed fuzzy rules are tabulated in Table 1.Using the fuzzy rules, the T_R^F is determined.

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Table 1: Fuzzy Rules for determining water temperature ratio T_R^F

e \ Δe	VBP	PB	PM	PS	ZE	NS	NM	NB	VBN
VBP	VBP	VBP	VBP	VBP	VBP	PB	PM	PS	ZE
PB	VBP	VBP	VBP	VBP	PB	PM	PS	ZE	NS
PM	VBP	VBP	VBP	PB	PM	PS	ZE	NS	NM
PS	VBP	VBP	PB	PM	PS	ZE	NS	NM	NB
ZE	VBP	PB	PM	PS	ZE	NS	NM	NB	VBN
NS	PB	PM	PS	ZE	NS	NM	NB	VBN	VBN
NM	PM	PS	ZE	NS	NM	NB	VBN	VBN	VBN
NB	PS	ZE	NS	NM	NB	VBN	VBN	VBN	VBN
VBN	ZE	NS	NM	NB	VBN	VBN	VBN	VBN	VBN

B. Determination of Water Temperature Ratio Using NN

NN is an artificial intelligence technique, used for generating training dataset and testing the applied input data. Here, a feed forward type NN is used for the proposed method. Normally, the NN consist of three layers: input layer, hidden layer and output layer. The input layer consist of two inputs i.e. error temperature 'e'and change of error temperature 'Δe'. The water temperature ratio 'T_R^{NN}' is the output of the NN. In NN, main process is performed in the hidden layer. The NN structure of the proposed water system is illustrated in Fig.2.

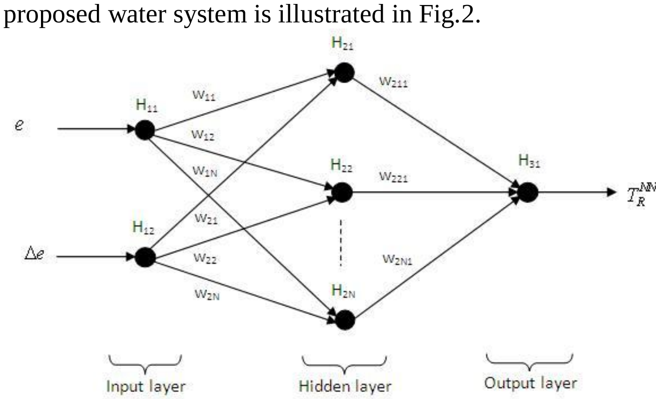

Figure 2: Structure of NN for Proposed Water Heating System.

In Fig. 3, the input layer, hidden layer and output layer of the network are (H_{11}, H_{12}), ($H_{21}H_{22}\ldots H_{2N}$) and$H_{31}$ respectively. Then, the weight of the input layer to hidden layer is denoted as $w_{11}, w_{12}, w_{1N}, w_{21}, w_{22}$ *and* w_{2N} respectively. The weight of the hidden layer to output layer is denoted as $w_{211}, w_{221}, w_{2N1}$ respectively. The network is trained by using the Back Propagation (BP) training algorithm.

The training steps involved in neural network are as follows,

Step 1: Initialize the input, output and weight of each neuron. Here, e and Δe are the inputs of the network and the water stream ratio 'T_R^{NN}'is the output of the network.

Step 2: The inputs of training dataset are e and Δe to the classifier and determine the BP error as follows,

$$BP_{err} = (T_R^{NN})_{tar} - (T_R^{NN})_{out} \quad (4)$$

In Eq. (4), $(T_R^{NN})_{tar}$ is the target output and $(T_R^{NN})_{out}$ is the network output.

Step 3: Calculate the network output as follows,

$$(T_R^{NN})_{out} = \alpha + \sum_{n=1}^{N} w_{2n1} T_R^{NN}(n) \quad (5)$$

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$$\text{Where, } T_R^{NN}(n) = \frac{1}{1+\exp(-w_{1n}e - w_{2n}\Delta e)} \qquad (6)$$

Eqn. (5) and (6) represents the activation function of output layer and hidden layer respectively.

Step 4: Adjust the weights of all neurons as $w = w + \Delta w$, where, Δw is the change in
Weight, which can be determined as

$$\Delta w = \gamma . T_R^{NN} . BP_{err} \qquad (7)$$

In Eq. (7), γ is the learning rate, usually it ranges from 0.2 to 0.5.

Step 5: Repeat the process from step 2, until BP error gets minimized to a least value i.e.,

$BP_{err} < 0.1$.

Once the process gets completed, the network is well-trained and it would be suitable for providing T_R^{NN} values for any error and change of error temperature.

These water stream ratio' T_R 'and T_R^{NN} is applied to the input of the condenser by adjusting the ACV and SV valve. In this way, the temperature of the water heating system is to be maintained.

V. RESULTS AND DISCUSSION

Based on the range of error temperature and change of error temperature, the water temperature ratio of the system is varied. From the range of temperature variation, the fuzzy rules are designed. The error and change of error temperature are applied to FLC and the water temperature ratio is determined. The membership function of error temperature, change of error temperature and water temperature ratio is described in Fig.3, Fig.4. The range of error is five to forty-five and change in error is -20 to 20. The Fig. 5 shows percentage of valve opening. Fuzzy inference system is generated and used for further prediction.

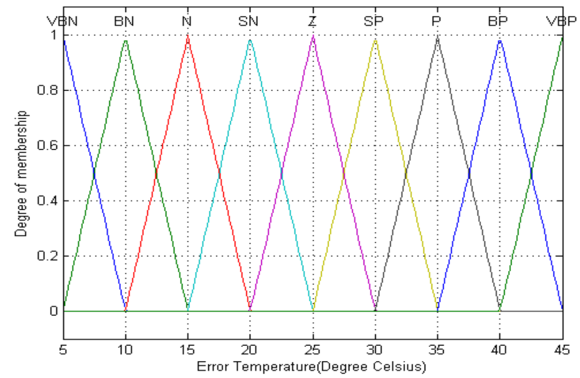

Figure 3: Membership Function of Error Temperature.

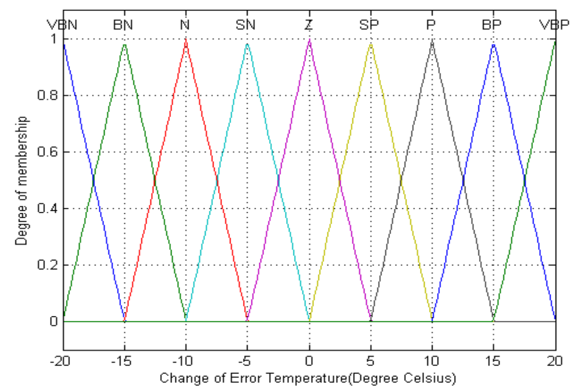

Figure 4: Membership Function of Change of Error Temperature.

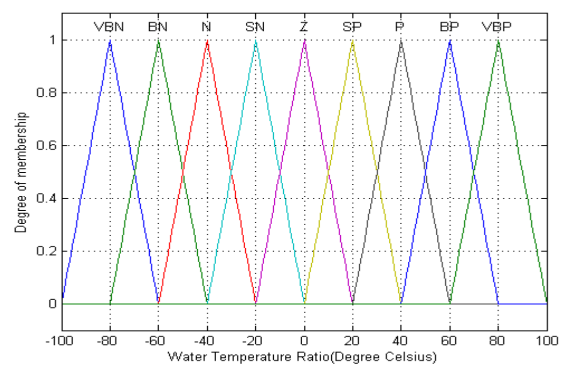

Figure 5: Membership Function of Water Temperature Ratio.

The structure of NN is described in Fig.6. The NN performance of Regression, validation and training state are shown in Fig.7.

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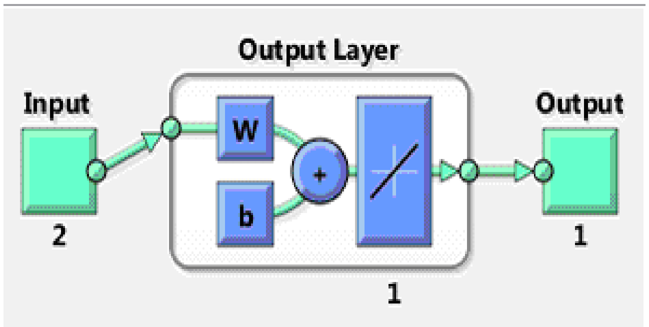
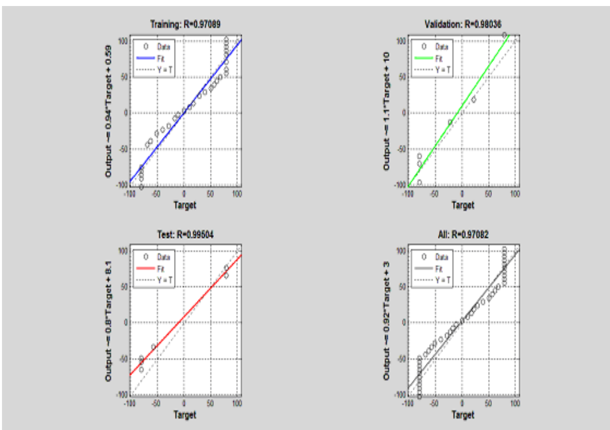
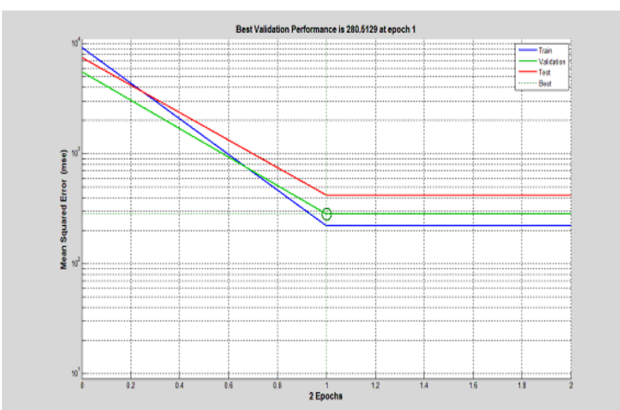


Figure 6: NN Structure of Proposed Water Heating System.



(i)



(ii)

Figure 7: NN Performance Plots (i) Regression Analysis, (ii) Network Validation performance.

A. Real Time Results

a. Fuzzy and ANN Results on Real Environment Set point =55°C settling threshold at 0.5 and 0.05

The system is tested in real environment for set point 55°C settling threshold at 0.5 and 0.05.To evaluate the performance of different controllers (models), the step response of the system have been considered. In all four controllers (models) the performance indices ISE, ITAE, MSE(mean square error) and MAE(mean average error), Transient response Rise Time, Settling Time, Settling Min, Settling Max. Overshoot, Under Shoot, Peak and Peak Time are taken for comparison. Total 985 readings for settling threshold at 0.5 and 0.05 were taken to test the performance of the system.

Hardware Setup Parameters:
Set Point = 55°C
Initial Temp = 39.9 °C
Temp of Hot water Tank = 91°C to 88°C
Inlet water flow = 100 ltr/s

Performance for Set Point 55°C

b. Settling band 0.5 degree

Figure 8 shows the performance graphs of output temperature variation Vs time for FUZZY and ANN for set point 55 degree and settling time band 0.5 respectively.

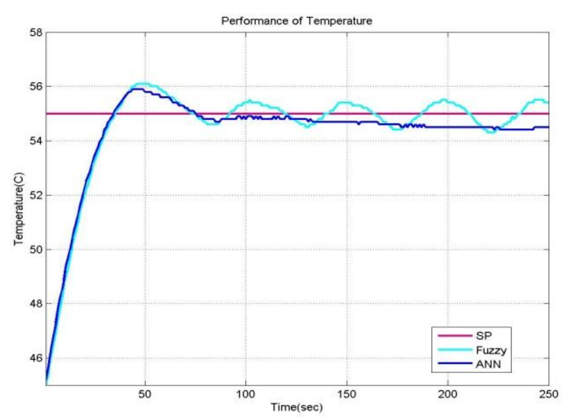


Figure 8 Comparison of Fuzzy and ANN

Table 2 summaries all the performance indices and Table 3 summarizes all transient responses of all models.

Table 2:Performance index for SP = 55 °C & Settling time Band = 0.5

Parameter	FUZZY	ANN
ITAE	**5.9e04**	**1.34e5**
ISE	**1.01e3**	**978.71**
MSE	**0.0012**	**0.0012**
MAE	**5.2680e-04**	**5.9996e-04**

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Table 2 shows error parameter ITAE of Fuzzy is $5.9*10^4$ which is less as compared to ANN. MAE(Mean average error), MSE are almost same. Transient response for the same is as shown in Table 3. Rise time and Settling time for Fuzzy and ANN is almost same.

Table 3: Transient Response for SP = 55 °C & Settling time Band = 0.5

Parameter	FUZZY	ANN
RiseTime	24.9750	24.5000
SettlingTime	12.16	12.7500
SettlingMin	54.2000	54.1000
SettlingMax	56.1000	55.9000
Overshoot	2.0000	1.6364
Undershoot	0	0
Peak	56.1000	55.9000
PeakTime	44	43

Table 3 shows the settling time of FUZZY and ANN is 12.16 and 12.75 respectively,

c. Settling band 0.05 degree

The performance graphs of output temperature variation Vs time for FUZZY, ANN, for set point 55 degree but settling time band 0.05 remains same as Fig 10. Table 4 summaries all the performance indices and Table 5 summarizes all transient responses of Fuzzy and ANN models.

Table 4 : Performance index for SP = 55 °C & Settling time Band = 0.05

Parameter	FUZZY	ANN
ITAE	5.9995e+004	1.3468e+005
ISE	1.0111e+003	978.71
MSE	0.0012	0.0012
MAE	5.2680e-004	5.9996e-04

.

Table 4 shows error parameter ITAE of Fuzzy is 5.99e+004which is less as compared to ANN. ISE, MSE are almost same.

Table 5: Transient Response for SP = 55 °C & Settling time Band = 0.05

Parameter	FUZZY	ANN
RiseTime	24.9750	24.5000
SettlingTime	870.1500	584.3000
SettlingMin	54.2000	54.1000
SettlingMax	56.1000	55.9000
Overshoot	2.0000	1.6364
Undershoot	0	0
Peak	56.1000	55.9000
PeakTime	44	43

Table 5 There is remarkable difference in settling time of Fuzzy and ANN. For ANN it is 584.30 sec and Fuzzy 870.25 sec. The variation in Settling Min and Settling Max is less, in case of ANN this clearly shows that FUZZY performance is slightly superior for 0.5 settling bandsas per the ITAE But ANN performance is good for higher resolution.

VI. CONCLUSION

The heat exchanger system has been modeled with various soft computing algorithms using Fuzzy and ANN. This paper shows a comparative analysis of controlling temperature of the heat exchanger using Fuzzy and ANN algorithms. The models were trained and tested on real time environment. The error and change in error are the inputs of controlling algorithm. The value of error is mapped in between 0 to 45 and change in error is mapped between -20 to +20. The algorithm gives output within a range -100 to +100, which is used for controlling action. The FIS structure is created with the help of Fuzzy rules generated by studying the mapping patterns between different linguistic variables. Generated FIS structure is used for testing. In case of ANN model the feed forward back propagation neural network is used as a controller. Network is trained with the help of Leven berg Marquart back propagation algorithm to maintain the desired temperature of heat exchanger. Artificial Neural network shows superior performance compared to Fuzzy as far as settling time of higher resolution is concern. For lower resolution performance is almost same. This concludes that hybridization of Fuzzy and ANN can gives better performance than both.

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