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Design and Simulation of Conventional and Intelligent Controllers for Temperature Control Of Shell and Tube Heat Exchanger System

E.Saranya and S.Arulselvi

Abstract— ***Heat exchanger system is widely used in chemical plants because it can sustain wide range of temperature and pressure. The main purpose of a heat exchanger system is to transfer heat from a hot fluid to a cooler fluid, so temperature control of outlet fluid is of prime importance. The designed controllers will regulate the temperature of the outgoing fluid to a desired set point in the shortest possible time irrespective of load and process disturbances, equipment saturation and nonlinearity. To control the temperature of outlet fluid of the heat exchanger system, a conventional P,PI and PID controller can be used. Due to nonlinear nature, shell and tube heat exchanger system is hard to model and control using conventional methods. The intelligent controllers are effective for nonlinear processes. In this paper, conventional P,PI,PID and IMC based PID controllers are designed and simulation results are presented and discussed. From the results it is observed that IMC based PID controller gives better results when compared to other controllers. To improve the performance the fuzzy controller and model based neuro controllers (inverse and internal model controllers) are designed and simulated. To develop model based neuro controllers forward and inverse neuro model are developed, trained and validated. Simulation studies are carried out with fuzzy logic controller and model based neuro controllers for servo and regulatory problems. The results are presented and discussed. It is observed that ,fuzzy logic controller and IMC based PID controllers are giving better results when compared to conventional PID controller and model based neuro controllers.***

Keywords— ***Shell and tube heat exchanger,IMC based PID controller, fuzzy, inverse controller , neuro IMC controller.***

I. INTRODUCTION

The transfer of heat to and from process fluids is one of the most basic unit operations in the processing industries. Heat exchangers are devices that facilitate efficient heat transfer between two media, thereby changing the temperature distribution of the two mediums when they are in direct or indirect contact [1]. They can transfer heat between a liquid and a gas (e.g., a liquid-to-air heat exchanger) or two gases (e.g., an air-to-air heat exchanger), or they can function as a liquid-to-liquid heat exchanger. It thus forms a integral equipment in a wide range of industries, including power generation, food processing, refrigeration, desalination, air conditioning, automobiles and electronics cooling. Due to nonlinear nature, shell and tube heat exchanger system is hard to model and control using conventional methods. In this paper, an average transfer function is obtained by giving positive and negative step changes in cold water inlet flow rate, to vary the hot water outlet temperature. For this transfer function, conventional P,PI,PID and IMC based PID controllers are designed and simulated. From the simulation studies, it is found that PID controller gives satisfactory performance. The PID controllers exhibits high overshoot which is undesirable. To reduce the overshoot and to optimize the control performance, an IMC based PID controller is designed and simulated. Due to inherent disadvantages of conventional control techniques, intelligent controllers are designed to control the temperature of outlet fluid of the heat exchanger system, intelligent controllers like fuzzy and neuro controllers are proposed and implemented [1]&[8]. From the results, it is observed that fuzzy and IMC based PID controller gives better result when compared to PID and neuro IMC controllers for both servo and regulatory problems.

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II. PROCESS DESCRIPTION

Shell and tube heat exchanger in their various construction modifications are probably the most widespread and commonly used basic heat exchanger configuration in the process industries. They provide a comparatively large ratio of heat transfer area to volume and weight and are easy to manufacture in a large variety of sizes and flow configurations. They can operate at high pressure and their construction facilitates disassembly for periodic maintenance and cleaning.

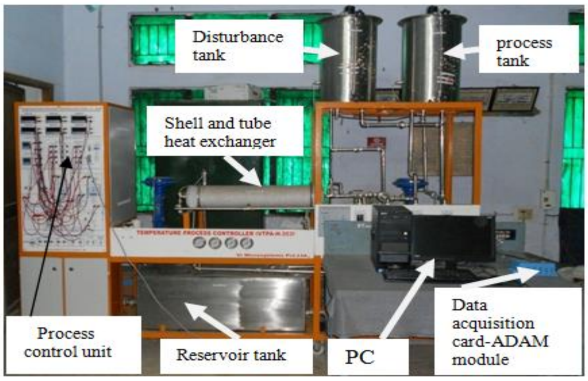
A shell and tube heat exchanger consists of a bundle of tubes enclosed within a cylindrical shell. One fluid flows through the tubes and second fluid flows within the space between the tube and the shell. Heat is thus transferred from one fluid to the other through the tube walls, either from tube side to shell side or vice versa. They can further be classified according to their flow arrangement. In co-current heat exchangers, the two fluids enter the exchangers at the fluids enter the exchanger from opposite ends. Most shell-and-tube heat exchangers are 1, 2, or 4 pass designs on the tube side depending upon the number of times the fluid in the tubes passes through the fluid in the shell.

A. Heat exchanger experimental set-up

The shell and tube heat exchanger setup used for study is shown in Fig.1. The system consists of 37 copper tubes of 750 mm length with a single pass arrangement.

The two fluid streams can be arranged both in co-current and counter current fashion.

The experiment is carried out using water as a single phase medium. In the process tank water is heated to a particular operating temperature. The hot fluid (water) then flows from the process tank and passes through the tube-side of the heat exchanger. Cold fluid (water) flows from the reservoir tank into the shell side of the heat exchanger. The disturbance tank is provided to study the performance of designed controllers for disturbance rejection.



There are two thyristor drives that regulate the voltage and current to the heaters in order to regulate the temperature of the water in process and disturbance tank. The cold and hot water inlet flow to the shell and tubes respectively are manipulated using pneumatic control valves. The flow rate of the hot water is treated as disturbance variable. The hot water inlet temperature is maintained with ± 0.5^0C variation using an inbuilt digital PID controller. The experiment is carried out in co-current mode. The hot water outlet temperature is considered as the controlled variable. whereas the cold water flow rate to the shell side is treated as the manipulated variable. The cold water is supplied at the room temperature. The inlet and outlet temperatures of the shell and tube side fluid are measured using the RTDs.

A differential pressure transmitter (DPT) is used to measure the cold water flow rate. The inlet flow of the cold water can be varied in the range of 0-350 LPH and that of hot water between 0-250 LPH. All the sensors and interfaced with a 16 bit data acquisition system (Advantech ADAM 5000 series hardware). A PC is used to log the data and also perform the functions of the controller. The process parameters are obtained from real time using MATLAB scientific package and the communication standard used is RS232. Fig.2 shows the photograph of the real time experimental setup and the specifications of the heat exchanger set up are tabulated in Table I.

TABLE I SPECIFICATION OF HEAT EXCHANGER SETUP.

COMPONENTS	SPECIFICATIONS
Shell Material	ss316
Shell Length	900mm
Shell Diameter	150mm
Tube Material	copper
Tube Length	750mm
Tube Diameter	4.6mm (ID),6.0 mm(OD)
Number of tubes	37
Number of passes	1
Pitch	triangular; 15mm
RTD Transmitter	Type : PT 100(3 wire),
	range:0-100^0C,Output:4-20mA
I/P converter	Input signal :4-20 mA,
	Output: 3-15 Psi
Control valve	Type : AIR TO CLOSE(cold fluid),
	AIR TO OPEN (hot fluid),
	Flow rate: 1000/5000 l/hr(max)
	Capacity : 75L,
	Characteristics: Equal percentage,
	input: 3-15Psi,
Disturbance tank with heater	Capacity :75L,
	Power:1.5 KW*2 with thyristor power driver
Reservoir tank	Capacity 250 L
Manipulated variable	0-300 LPH
Process variable	°C 42-51

B. *Procedure for obtaining process parameters*

The process reaction curve can be obtained by giving a step change in the manipulated variable. It is one of the widely followed process identification technique [2] and [3]. This method is used for identifying parameters of the shell and tube heat exchanger at each region. For each of these regions a step change in cold water inflow rate is given in both positive and negative directions and the corresponding reaction curves are obtained as shown in Fig.2.

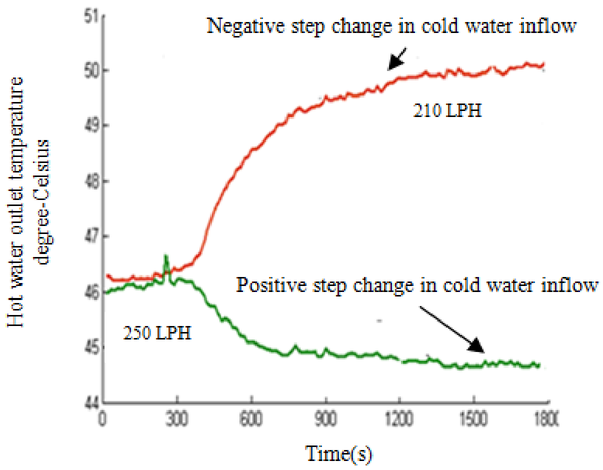


Fig.2. Process reaction curve to obtain the transfer function.

The transfer functions obtained are tabulated in TABLE II. Using average transfer function ,the controller parameters are obtained. The Ziegler–Nichols rule often leads to a rather oscillatory response to set point changes. According to Zeigler-Nichols tuning, the controller parameters are obtained and tabulated in Table III.

TABLE II AVERAGE TRANSFER FUNCTION

TRANSFER FUNCTION	AVG TR.FN
140LPH to 70 LPH	$g_p(s)=\frac{-0.03675}{153s+1}e^{-60s}$
$g_p(s)=\frac{-0.021}{90s+1}e^{-67.5s}$	
140LPH to 70 LPH	
$g_p(s)=\frac{-0.0525}{216s+1}e^{-52.5s}$	

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TABLE III THE P,PI AND PID CONTROLLERS SETTING FOR SHELL AND TUBE HEAT EXCHANGER

Controllers	k_c	k_i	k_d
P	-69.38	*	*
PI	-62.44	-0.3125	*
PID	-83.26	-0.693	-2497.8

The simulations are carried out using P,PI and PID controller parameters as tabulated in Table III . The responses are obtained as shown in Fig.3.

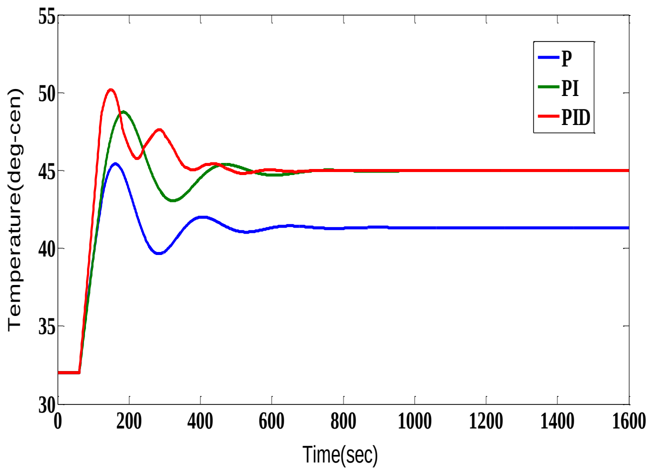

Fig.3. Response of conventional P,PI and PID controllers for a set point of 45°c.

TABLE IV SERVO PERFORMANCE MEASURES OF P,PI AND PID CONTROLLERS

Controllers	%Mp	Ts (sec)	Offset	ISE
P	9.44	1012	3.6	3.353×10^4
PI	8.34	929	*	1.518×10^4
PID	11.56	800	*	1.472×10^4

From the responses, it is observed that the P controller produces lesser overshoot, large settling time and more ISE value and also offset. The offset is eliminated, the settling time and ISE value is also reduced when implementing PI controller. From the PID controller, it is observed that even though the overshoot is higher, settling time and ISE value is much reduced when compared to P and PI controller.The performance of P,PI and PID controllers are tabulated in Table IV . From the Table, it is observed that PID controller gives better response compared to P and PI controllers.

To improve the performance measures of conventional controllers, IMC based PID structure is implemented. The IMC based PID structure compensates disturbance and model uncertainty. The IMC based PID tuning factor lambda is used to detune for model uncertainty. The IMC based PID controller has one tuning parameter lambda.

III. THE IMC STRATEGY

The IMC structure is shown in Fig.4.The distinguish character of this structure is the process model, which is in parallel with the actual process (plant) and that (~) is generally used to represent signals associated with the model.

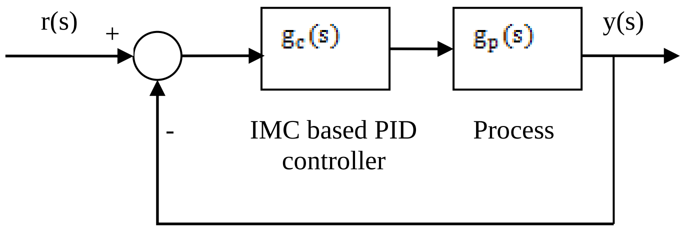

Fig.4.The Internal Model based PID Controller Structure.

A. *Design Procedure For Imc- Based Pid Controller*

In order to arrive at a PID equivalent form for process with a time delay, a approximation is taken to the dead time and adding filter as given by

$$q(s)=\tilde{q}(s)=f(s)=\tilde{g}_{p-}^{-1}(s)f(s) \qquad (1)$$

$$=\frac{(\tau_p s+1)(0.5\theta s+1)}{k_p}\frac{1}{(\lambda s+1)} \qquad (2)$$

The PID equivalent is

$$g_c(s)=\frac{q(s)}{1-\tilde{g}_p(s)q(s)} \qquad (3)$$

$$g_c(s)=\frac{\tilde{q}(s)f(s)}{1-\tilde{g}_{p-}(s)\tilde{g}_{p+}(s)\tilde{g}_{p-}^{-1}(s)f(s)} \qquad (4)$$

Referring Table II,

$$g_c(s)=\left(\frac{-1}{0.03675}\right)\frac{(153S+1)(30S+1)}{(\lambda+30)S} \qquad (5)$$

compare the equation (5) with the ideal PID controller as given

$$\left[\frac{K_dS^2+K_cS+K_i}{S}\right] \qquad (6)$$

$$K_c = \frac{(153+30)}{(0.03675)(\lambda+30)} = -46.75 \qquad (7)$$

$$\tau_i = \tau_p + \theta = 153+30 = 183;\ K_i = -0.225 \qquad (8)$$

$$\tau_D=\frac{\tau_p\,\theta}{2\tau_p+\theta} = \frac{153\times60}{(2\times153)+60} = K_d = -1172.49 \qquad (9)$$

The q(s) is proper if the process order is first order plus delay and a good rule-of thump is to choose λ to be twice as fast as the open loop response. Hence, $\lambda=76.5$.

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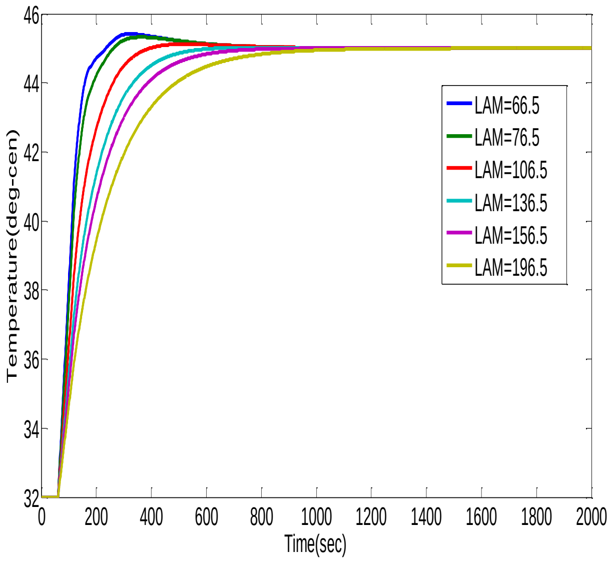

Fig.5.Response of conventional IMC based PID controller for different lambda values.

TABLE V PERFORMANCE MEASURES OF IMC BASED PID CONTROLLER

λ	IMC BASED PID CONTROLLER		
	%M_P	**T_S (sec)**	**ISE**
66.5	0.94	800	1.491×10^4
76.5	0.72	1188	1.551×10^4
106.5	0.27	848	1.749×10^4
136.5	0.04	588	1.965×10^4
156.5	*	970	2.115×10^4
196.5	*	1590	2.417×10^4

Fig.5 shows the response of internal model based PID controller in shell and tube heat exchanger system with different values of filter parameter.The IMC based PID controller has given in equation 7,8 and 9 is simulated for various lambda values and the response are shown in Fig.5.For various lambda, the performance measures of IMC controller is tabulated in Table V. From the Fig.5 it is observed that optimum lambda is found to be 136.5 by compromising the ISE value and settling time. When compared to PID controller, IMC based PID controller gives better performance as seen from Fig. 5 and Table V. The overshoot, settling time and ISE values are very much reduced. The designed internal model based PID controller is very much effective because it shows very less overshoot and has only one tuning parameter, lambda

IV. FUZZY LOGIC CONTROLLER

The structure of intelligent fuzzy controller is shown in Fig.6.

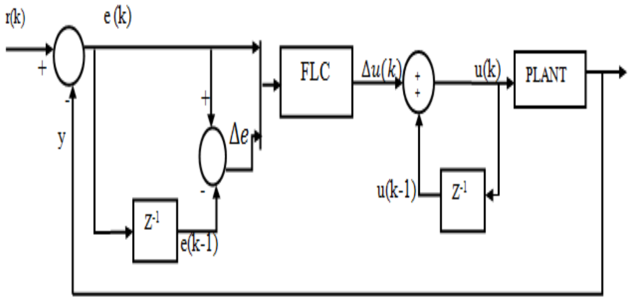

Fig.6. Block diagram of fuzzy logic controller.

The design of fuzzy logic controller is attempted in heat exchanger. The fuzzy controllers are designed with two input variables, error and change in error and one output variable (i.e) the cold water flow rate to the shell side. The mamdani based fuzzy inference system uses linear membership function for both inputs and outputs. For the classical fuzzy logic controller the input variable are error (e) and change of error (Δe), the output variable is the change in controller output(Δu). Triangular membership functions are used for input variables and the output variable. The universe of discourse of error, change in error and output are [-13, 13], [-0.1, 0.1] and [-5, 5] respectively. The rule base framed for shell and tube heat exchanger are tabulated in Table VI.

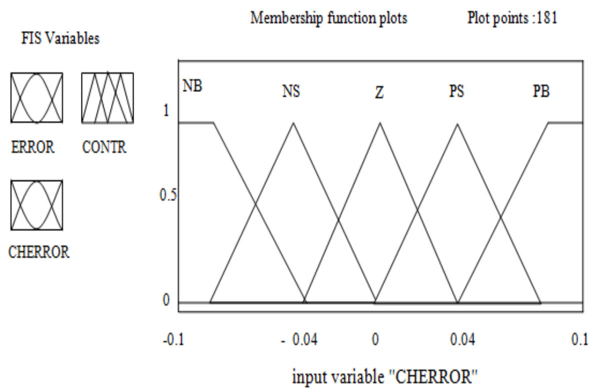

Fig. 7. Membership function for error.

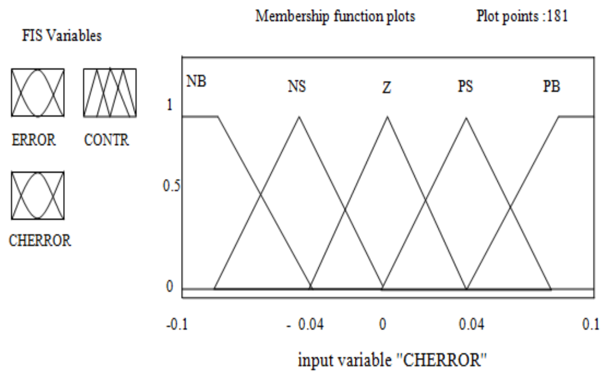

Fig. 8. Membership function for change in error.

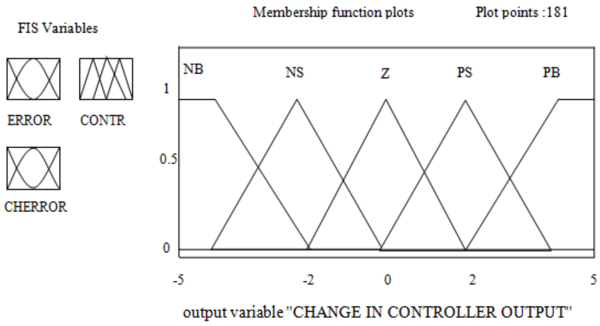

Fig. 9. Membership function for change in controller.

The membership function for error, change of error and change of controller output consist of negative big (NB), negative small (NS), zero (Z), positive small (PS) and positive big (PB). The complete set of classical fuzzy logic control rules given in table VI.

This structure of the rule base provides negative feedback control in order to maintain stability under any condition. For the evaluation of the rules, the fuzzy reasoning unit of the FLC has been developed using the Max-Min fuzzy inference method. In the particular FLC, the centroid defuzzification method is used.

TABLE VI FUZZY ASSOCIATIVE MEMORY FOR FLC

Cherror (Δe) / Error (e)	NB	NS	Z	PS	PB
NB	PB	PB	PS	PS	Z
NS	PB	PS	PS	Z	NS
Z	PS	PS	Z	NS	NS
PS	PS	Z	NS	NS	NB
PB	Z	NS	NS	NB	NB

The simulated servo response for fuzzy logic controller is shown in Fig.10 for a set point of 45°c. The performance measures are tabulated in table VII.

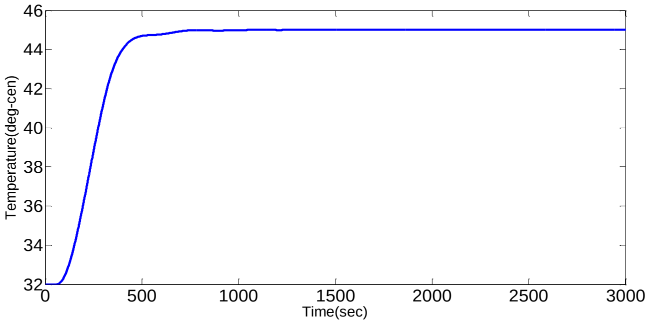

Fig.10.Servo response of fuzzy logic controller for the set point of 45°c.

The simulated step response for fuzzy logic controller is obtained for a various set point of 45 to 48 to 51 is shown in Fig.11. The performance measures are tabulated in Table VII for the range of 48 to 51 °c.

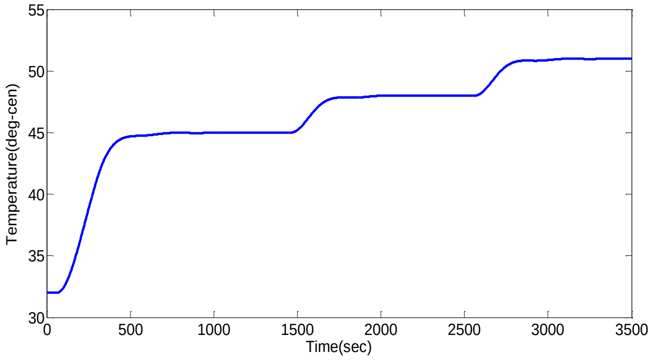

Fig .11. Step response of intelligent fuzzy logic controller

The simulated regulatory response for fuzzy logic controller is obtained for a set point of 45°c with load disturbance of 3°c is shown in Fig.12. The performance measures are tabulated in Table VII.

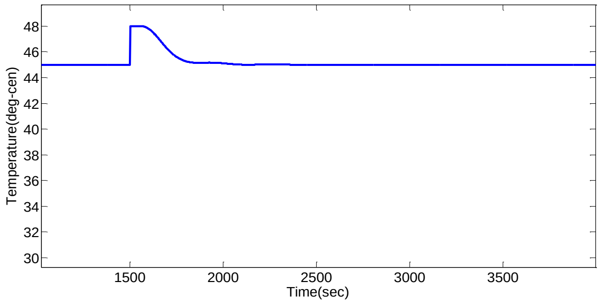

Fig.12.Regulatory response of intelligent fuzzy logic controller for a set point of 45°C and load disturbance of 3°C.

TABLE VII PERFORMANCE MEASURES FOR SERVO AND REGULATORY PROBLEMS WITH FUZZY LOGIC CONTROLLERS.

CONTROLLER	%M_P	T_S(sec)	ISE
FUZZY(servo) for 45°C	*	1263	3.332×10^4
FUZZY(servo) for 48 to 51°C	*	980	1388
FUZZY(regulatory)	*	880	1391

From the obtained servo response, it is observed that fuzzy controller having no overshoot when compared to conventional PID controller.

V. NEURAL MODELING AND CONTROLLERS

A. Generation of input output data

The forward neuro model is trained and validated by giving repeating stair sequence in cold water flow and the corresponding hot water outlet temperature are obtained as shown in Fig.14.

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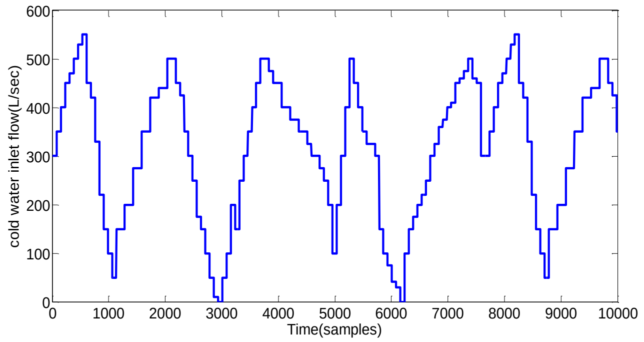

Fig .13. Actual input

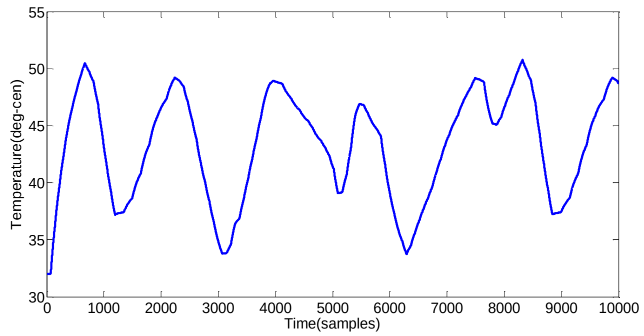

Fig.14. Actual process output

The identification of data sample containing 10001 samples with sampling time of 75 sec.

B. Forward modeling for neural network

To capture the nonlinear dynamics of shell and tube heat exchanger as it is, delayed input and outputs are used. Forward neuro model is obtained by using delayed outputs and delayed input. Cold water inflow rate (C_{in}) and hot water outlet temperature (T_{ho}) values are considered for developing a forward model of the shell and tube heat exchanger .The block diagram of forward model as shown in Fig.15.

The parameters used for forward modeling

Input vectors : $[T_{ho}(k-1)\ T_{ho}(k-2)\ C_{in}(k-1)]$

Output vector : $\hat{T}_{ho}(k)$

Sampling interval : 75 sec

Training algorithm : BPN Algorithm

Activation function : 1.Hidden layer-Tan –sigmoid function,

$$f(x)=\frac{1-\exp(-x)}{1+\exp(-x)}$$

2. Output layer-Pure linear function

Learning rate : 0.001

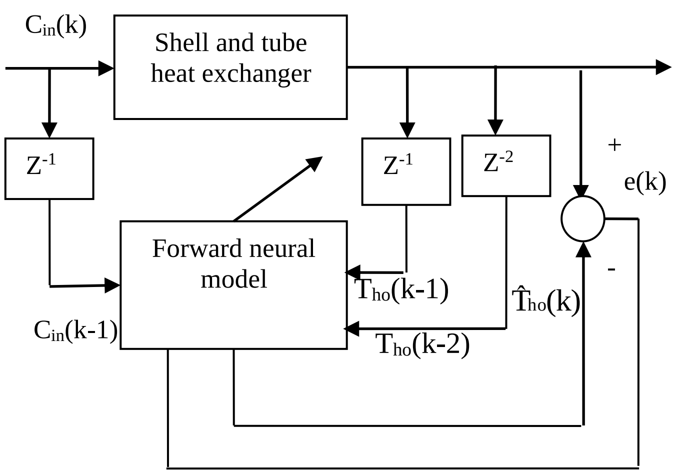

Fig.15. Block diagram of feed forward neural model of shell and tube heat exchanger process.

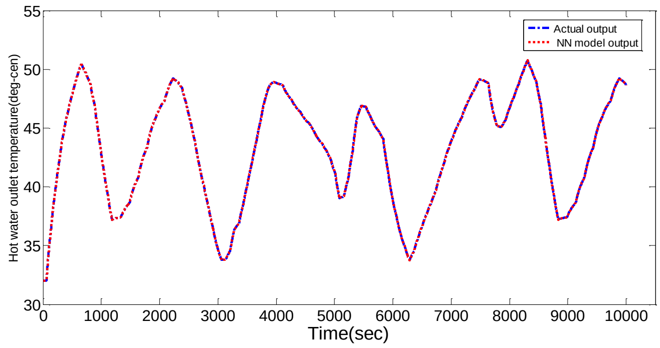

Fig.16. Output response of feed forward neural network compared with the actual process output.

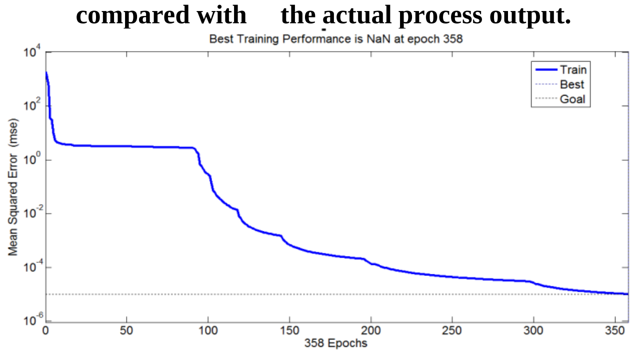

Fig.17. Performance response of feed forward neural network.

The corresponding change in the output of actual model are given as input to the forward model. Then the model output is compared with the actual process output. It is clear from the Fig.16 that the forward model output exactly matches with output of the actual model. Hence the neural network has the ability to model forward dynamics of the shell and tube heat exchanger process, which can be used for developing the model based controllers.

C. Inverse modeling for neural network

Inverse neuro model is obtained by using delayed outputs and delayed input. Cold water inflow rate (C_{in}) and hot water outlet temperature (T_{ho}) values are considered for developing a inverse model of the shell and tube heat exchanger .The block diagram of inverse model as shown in Fig.18.

The parameters used for inverse modeling :
Input vectors:
Output vector :
Sampling interval $\hat{C}_{in}(k)$: 5 sec

Training algorithm : BPN Algorithm

Activation function : 1.Hidden layer-Tan –sigmoid function,

$$f(x)=\frac{1-\exp(-x)}{1+\exp(-x)}$$

2. Output layer-Pure linear function

Learning rate : 0.001

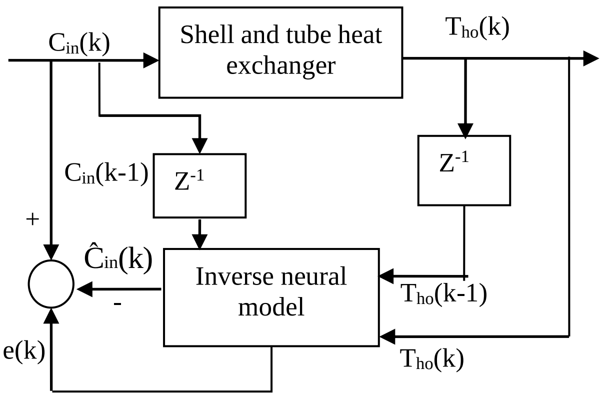

Fig.18. Inverse neural model.

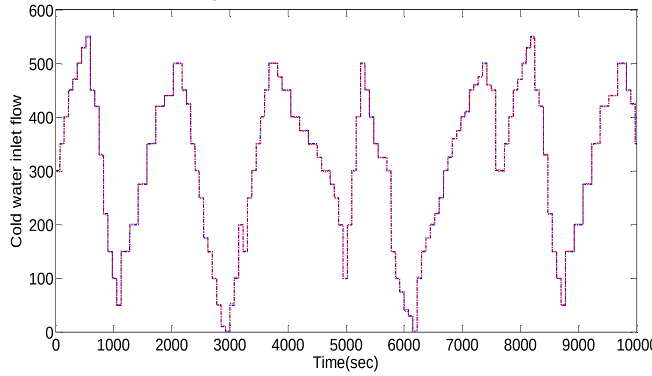

Fig.19. Output response of feed forward neural network compared with the actual process output.

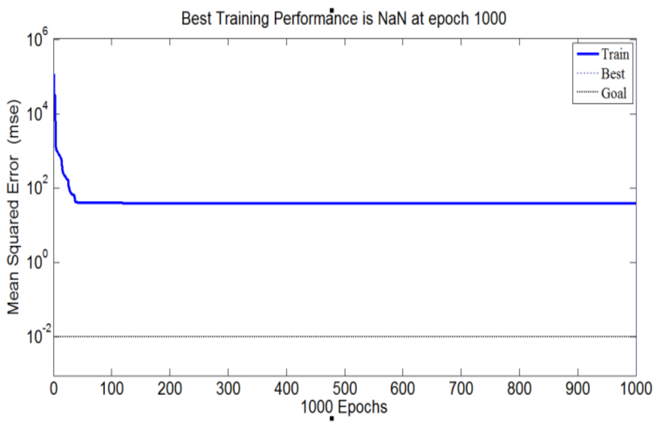

Fig.20.Performance response of inverse neural network.

Then the model output is compared with the actual process input. It is clear from the Fig.19 that the inverse model output exactly matches with input of the actual model. Hence, the neural network has the ability to model inverse dynamics of the shell and tube heat exchanger process, which can be used for developing the model based controllers.

D. Inverse controller

The advantage of using inverse control is that it does not require an existing controller. The inverse model developed is connected in cascade with the shell and tube heat exchanger as shown in Fig.21. The inverse controller cancel out the nonlinearities in the shell and tube heat exchanger.

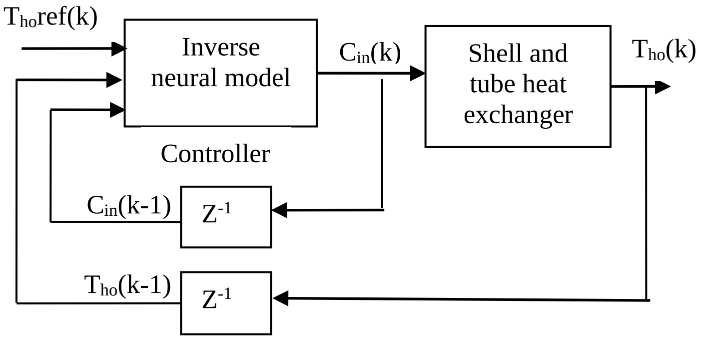

Fig.21.Block diagram of inverse control.

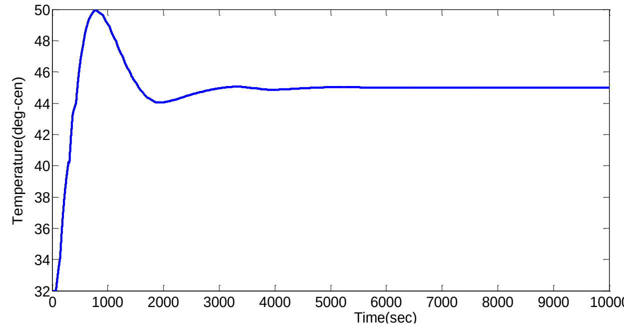

Fig.22.Servo response of inverse control.

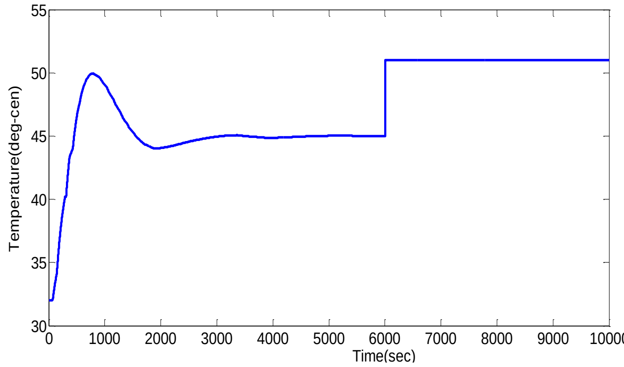

Fig.23.Regulatory response of inverse control.

The effectiveness of the inverse neuro control is verified for set point tracking as shown in Fig.22. The controlled system could follow the set point very well. However this control technique will not work for load disturbances as shown in Fig.23. Hence, an IMC is developed using neuro models to regulate the hot water outlet temperature (T_{ho}) value against set point tracking and load disturbances.

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E. Neuro IMC controller

The problems associated with inverse control such as process-model mismatch is reduced using the neuro IMC. The structure of neuro IMC developed for shell and tube heat exchanger is shown in Fig.24.

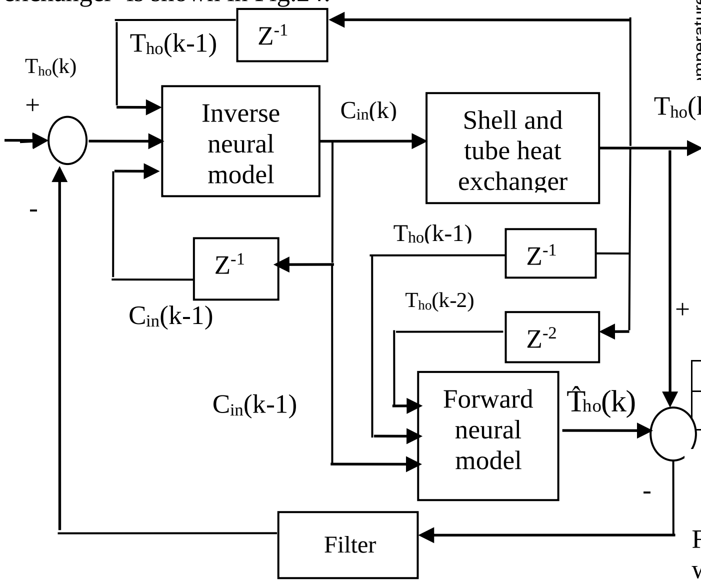

Fig.24.Block diagram of neuro Internal Model Controller.

The performance of the controller is verified for set-point tracking and load variation. The servo and regulatory response for neuro IMC is shown in Fig.25 and Fig.26 respectively. The performance measures are tabulated in Table VIII.

VI. RESULTS AND DISCUSSION

The simulated servo response of shell and tube heat exchanger process for neuro IMC controller shows the good set point tracking comparable to the inverse control as shown in Fig.25. The performance measures of the controllers are given in Table VIII.

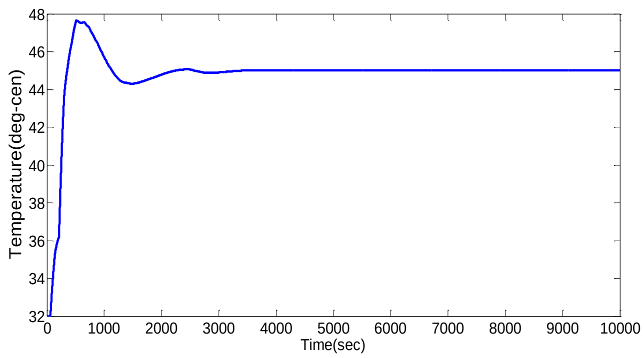

Fig.26.Servo response of neuro IMC controller.

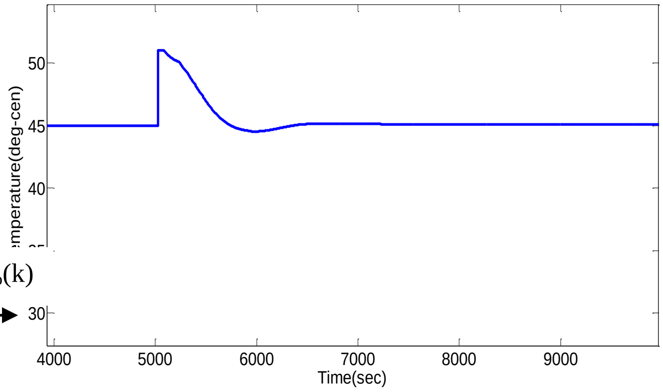

Fig.27.Regulatory response of neuro IMC controller.

TABLE VIII PERFORMANCE MEASURES OF NEURO IMC CONTROLLER

CONTROLLERS	%MP	TS	ISE
NEURO IMC(SERVO)	5.90	3478	2.908×10^4
NEURO REGULATORY)	0.94	2250	1.954×10^5

From the obtained response it is observed that neuro IMC work for both servo and regulatory problems.

VII. SIMULATION RESULTS

A. Servo response

From the servo responses as shown in Fig.27 and the corresponding performance measures as given in Table IX of PID, IMC based PID, fuzzy and neuro IMC controllers, it is observed that IMC based PID controller and fuzzy logic controllers gives better result when compared to other controllers.

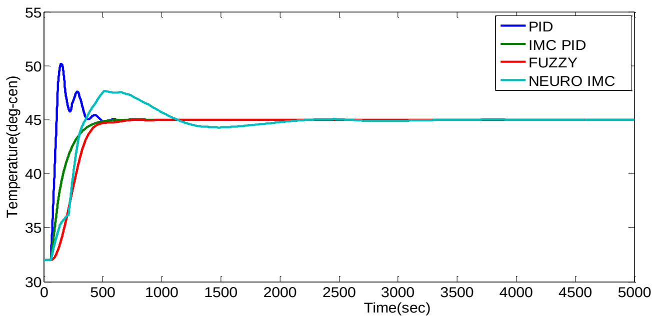

Fig.27.Servo response of PID,IMC based PID, FUZZY and neuro IMC controllers.

TABLE IX
SERVO PERFORMANCE MEASURES OF PID, IMC BASED PID,FUZZY AND NEURO IMC CONTROLLERS FOR THE SET POINT OF 45°C

CONTROLLERS	%MP	TS	ISE
PID		942	1.472×10^4
IMC PID	*	1126	1.965×10^4
FUZZY	*	1263	3.332×10^4
NEURO IMC	5.90	3478	2.908×10^4

The step response of conventional PID, IMC baased PID and intelligent fuzzy controllers for various step responses of 45 to 48 to 51 are given and compared with intelligent neuro IMC controller. From the step responses as shown in Fig.28 and the corresponding performance measures as given in Table XI, it is observed that IMC based PID controller and fuzzy gives better result when compared to other controllers.

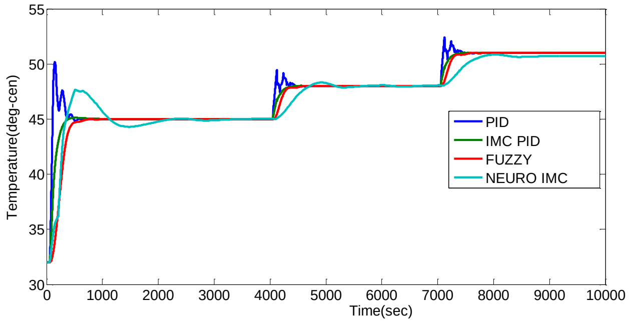

Fig.28.Step response of PID, IMC BASED PID,FUZZY and neuro IMC controllers.

TABLE X
PERFORMANCE MEASURES OF PID, IMC BASED PID,FUZZY AND NEURO IMC CONTROLLERS FOR THE RANGE OF 48 TO 51°C

CONTROLLERS	%M_P	T_S	ISE
PID	9.39	1180	651.8
IMC PID	*	595	853
FUZZY	*	980	1388
NEURO IMC	5.93	1980	31.76

B. Regulatory responses

From the regulatory responses as shown in Fig.29 and the corresponding performance measures as given in Table X of PID, IMC based PID, fuzzy and neuro IMC controllers, it is observed that IMC based PID controller and fuzzy logic controller gives better result when compared to other controllers.

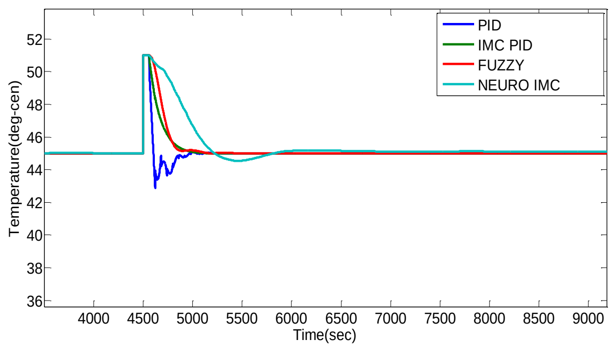

Fig.29.Regulatory response of PID,IMC based PID,fuzzy and neuro IMC controller

TABLE XI
REGULATORY PERFORMANCE MEASURES OF PID, IMC BASED PID,FUZZY AND NEURO IMC CONTROLLERS

CONTROLLERS	%M_P	T_S	ISE
PID	36.13	732	650.7
IMC PID	*	665	973.6
FUZZY	*	880	1391
NEURO IMC	0.94	2250	1.954×10^5

VIII CONCLUSION

In this work, the conventional PID,IMC based PID, and intelligent fuzzy, neuro controllers are developed for a shell and tube heat exchanger system. When comparing the performance of PID, IMC based PID, Fuzzy and neuro IMC controllers, it is observed that IMC based PID and fuzzy controller gives better performance than PID and neuro IMC controllers for both servo and regulatory problems in terms of overshoot, settling time and ISE value. Therefore the fuzzy logic and IMC based PID controllers are working properly for both servo and regulatory problems.

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