REAL TIME CONTROL OF A SHELL AND TUBE HEAT EXCHANGER BY IMPLEMENTING ANFIS MODEL REFERENCE ADAPTIVE PID CONTROLLER

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Abstract

In this work ANFIS MRA PID controller was implemented in a shell and tube heat exchanger (STHE) and the temperature of hot water flow of the heat exchanger was controlled. The second order differential equation model of the heat exchanger was used to carry out the simulation studies of proposed controller for servo and regulatory tracking of the system. The performance of the proposed controller found better when compared with conventional PID and FMRAC controlled responses of the system. The real time control implemented on STHE system using the proposed controller also proved its better performance than the real time performance of the STHE system implemented with conventional PID controller

Keywords: STHE control; ANFIS MRA-PID, FMRA-PID, MRA-PID

1. Introduction

Heat exchanger plays a vital role in maintaining temperature of various constituents of a chemical process to obtain the product at required quality. Shell and tube heat exchanger (STHE) is most commonly used heat exchanger to control temperature of liquids. It is essential and unavoidable to implement proper control strategy for highly non linear STHE systems for its efficient control of process liquid temperature. The conventional PID controller[1] requires off-line re-tuning procedures of controller gain parameters whenever the process conditions get altered thus creates a time delay in the production process. The problem can be overcome by implementing online tuning process of PID controllers through adaptive control schemes [3]. This paper discuss about the performance of STHE system implemented with ANFIS based adaptive control scheme. The control strategies are implemented using matlab at simulation level and in real time STHE experimental setup. The real time implementation of ANFIS MRA PID controller using matlab on STHE setup is achieved through Adavantech ADAM 5000 series data acquisition system. The performance of the STHE process with proposed controller is observed for servo and regulatory actions and compared with fuzzy based MRAC and conventional PID controller strategies.

2. EXPERIMENTAL SETUP

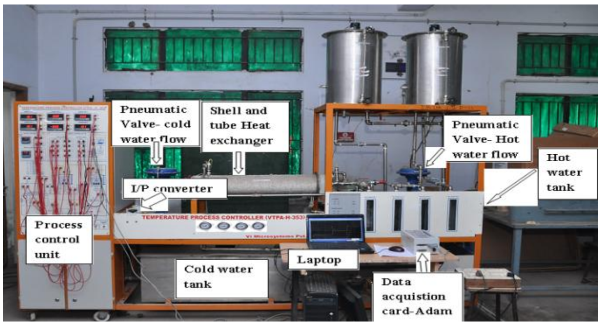

Fig 1. Experimental setup of shell & tube heat exchanger

The experimental setup of shell & tube heat exchanger is as shown in Fig 1. The STHE experimental setup was designed to test the performances of various advanced control strategies in the control of process liquid temperature through heat exchange. The experimental setup replicates an industrial STHE system. The setup was fabricated with 37 copper tubes of 750mm length and a shell arrangement with a single pass arrangement. The two fluids hot or process fluid and coolant fluid can be operated in either co-current or in counter current fashion. Water is used as a single phase medium to carry out the experiments. A process tank incorporated with a local PID based temperature control system supported with R.T.D supplies hot water at constant temperature to the tubes of heat exchanger. The flow rate of the hot fluid was kept constant by means of a control valve in the flow path of hot fluid. The fluid flow line from process tank also connected with a disturbance flow line with flow control mechanism to vary the process fluid flow rate to observe the regulatory responses. The cold fluid from the reservoiur enters into shell region of heat exchanger through a flow regulating control valve. The inflow rate of hot fluid can be varied between (0-250) LPH and cold fluid can be varied between (0-350) LPH. The flow rates of hot and cold fluid were measured using separate differential pressure flow transmitter. The functions of controller are performed using a Matlab package installed in a personal computer. The controller was interfaced in real time with sensing and controlling elements of the STHE experimental system through a 16-bit Advantech ADAM 5000 series data acquisition system. In this work the hot fluid temperature is considered as controlled variable and cold fluid flow rate is considered as manipulated variable

3. STHE Model

The two major sections of STHE were shell and tube.
the energy balance equation for the shell sector and tube sector were arrived by having the following assumptions, the sectors have smaller control volumes, maintained at fixed temperature and the unit is perfectly insulated so that there will not be heat loss to the surroundings from the heat exchanger. In STHE the rate of energy stored in the control volume is equal to the rate of gain of energy from neighbouring control volume.

The energy balance equation of shell control volume is given by

$$\frac{\rho_s c_s v_s}{N} * \frac{dT_{co}}{dt} = m_s c_s \left(T_{ci} - T_{co}\right) + \frac{h_s A_s}{N} \left(T_{ho} - T_{co}\right) \qquad (1)$$

The energy balance equation on the tube control volume is given by

$$\frac{\rho_t c_t v_t}{N} * \frac{dT_{ho}}{dt} = m_t c_t \left(T_{hi} - T_{ho}\right) + \frac{h_t A_t}{N} \left(T_{co} - T_{ho}\right) \qquad (2)$$

Based on the STHE experimental setup the input values of heat exchanger mathematical model are as listed in table.1

Table-1
Input values for STHE mathematical model

Parameters	Magnitude	unit
Water specific heat capacity(C_s, C_t)	4230	J/Kg/ ° C
Liquid or water density (ρ_s, ρ_t)	1000	Kg/m3
Area of heat transfer in shell (A_s)	0.29	m2
Volume of shell part (V_s)	2.52 X 10-4	m3
Shell part heat transfer coefficient (h_s)	2162	W/m2 ° C
Area of heat transfer in tube (A_t)	0.264	m2
Volume of tube part (V_t)	1.31 X 10-4	m3
Tube part heat transfer coefficient (h_t)	2162	W/m2 ° C
Cold water mass flow rate (m_s)	0-0.1	Kg/S
Inlet temperature of cold water (T_{ci})	34	° C
Hot water mass flow rate (m_t)	0.29	Kg/S
Inlet temperature of hot water(T_{hi})	60	° C
Control volume count(N)	10	N/A

4. Determination of STHE controller parameters

The parameters of STHE system were derived using process reaction curve method. The entire non linear operating region of STHE system was split into three smaller linear regions. For each region the process parameters were estimated by recording ‘S’ shaped response of STHE of outlet hot water temperature. The response was obtained for each region by disturbing the steady state operating condition of STHE through a unit change in the inflow rate of coldwater. The steady state is disturbed by introducing increasing and decreasing the cold water flow rate of equal magnitude and the responses were recorded for all cases.

Because of the non linearity associated with the STHE system the variation in the temperature of hot water outlet (Tho) will not be same for the unit step change given in increasing and decreasing order. So for estimation of process parameters average of KP and τP were estimated. The temperature of outlet hot water (Tho) was observed to be rising for fall in the inflow rate of the cold water because of this characteristic negative process gain was observed for almost all regions. The time constant τP (sec), gain of the process KP (°C/LPS), and dead time td (sec) for all three regions are tabulated in Table 2. The variation in time constant and steady state gain results to non linear behaviour for STHE can be viewed clearly in Table 2. For all the three regions the mean of KP, τP, & td are calculated and summarized.

Table 2
STHE system parameters

Region	Process Gain KP(°C/LPS)	Time constant τP (sec)	Dead Time td (sec)
Region 1 (48- 50°C)	-40.5101	0.5022	0.1123
Region 2 (50- 52°C)	-106.1222	0.7314	0.1298
Region 3 (52- 54°C)	-201.8863	0.9626	0.1395

From the Table 2, worst case transfer function is obtained as

$$G_p(s) = \frac{-201.8863}{0.5022s + 1} e^{-0.1395\ S} \qquad (3)$$

From the worst case model, PID controller parameters; proportional gain KC, Integral time Ti and Derivative gain Kd=Td are calculated using open loop tuning method of Zeigler–Nichols (Z-N) and are listed in Table 3.

Table 3
PID Controller parameters of shell and tube heat exchanger

Controller mode	Proportional gain KC	Integral Time Ti (sec)	Derivative time Td (sec)
PID	-0.0213	0.279	0.06975

5. Model Reference Adaptive PID Control

In this part MIT rule based design of parameter adaptation laws for PID control algorithm were discussed [4]. The MRAC control was used here as the parameters of the plant and disturbance rate of variation were found to be slower than the plant dynamic behaviour. The structure of model reference adaptive control scheme is pictured in fig 2. The MIT rule was utilized for determining [5] the adaptation law for controller and for tracking error. The controller parameters were adjusted through the adjustment or adaptive mechanism by utilizing the control parameter θ

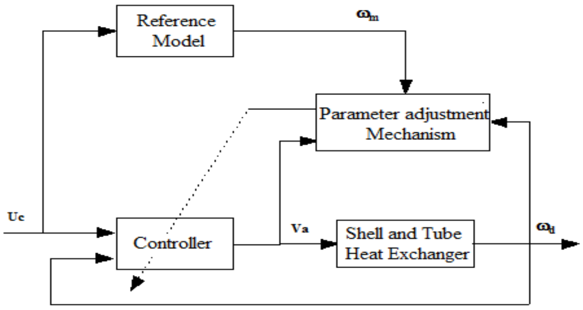

Fig 2. Model Reference Adaptive PID Controller structure

According to the definition of MIT rule the negative gradient of cost function (J) is proportional to rate of changes in θ, in other way

$$\frac{d\theta}{dt} = -\gamma\frac{\partial J}{\partial\theta} = -\gamma\epsilon\frac{\partial\epsilon}{\partial\theta} \qquad (4)$$

The adaptation error; $\varepsilon = y_p(t) - y_M(t)$. The shell and tube heat exchanger hot water outlet temperature y_p was made to follow a desired trajectory y_M, generated by the reference model of the MRAC. The reference model was defined as regular second order differential equation defined by

$$H_M(s) = \frac{b_M}{s^2 + a_{M1} + a_{M0}} \qquad (5)$$

With respect to the adjustable parameter vector, $\frac{d\in}{d\theta}$ will be the sensitive derivative of error. The adaptation gain is defined as γ. From the cost function utilizing the MIT rule as gradient mechanism the squared model error $\in^2$ was minimized [6] and can be given as

$$J(\theta) = \frac{1}{2}\varepsilon^2(t) \qquad (6)$$

the adaptive law of MRAC structure was taken as

$$u(t) = \left(K_p e(t) + K_i \int e(t)dt - K_d e^*(t)y_p\right) \qquad (7)$$

If error $e(t) = u_c - 1$, proportional mode gain= K_p, reset controller mode gain = K_i, derivative mode =K_d gain and step input = u_c. Equation (7) was represented in laplace domain as

$$U(s) = \left(sK_pE + K_iE - s^2K_dE\right) \qquad (8)$$

Now, closed loop transfer function of the system with control law was given by

$$Y_p = G_p\left(\left(K_p + \frac{K_i}{s}\right)(u_c - y_p) - sK_dy_p\right) \qquad (9)$$

The equation (10) for tracking error is satisfied by estimating the parameters K_P, K_i, K_d of the PID controller using MIT rule

$$\in = \frac{U_c(G_pK_p + G_pK_i)}{\left(s^2G_pK_d + s(1 + G_pK_p) + G_pK_i\right)} - Y_M \qquad (10)$$

The formulas derived from MIT rule was utilized with minimum approximation in plant and reference model denominators. The parameters closed to ideal values were given as

$$\frac{dK}{dt} = -\frac{\partial J}{\partial K_i} * \gamma = -\left(\frac{\partial J}{\partial\epsilon}\right)\left(\frac{\partial\epsilon}{\partial Y}\right)\left(\frac{\partial Y}{\partial K}\right) * \gamma \qquad (11)$$

and

$$\epsilon = \frac{\partial J}{\partial\epsilon} \text{ with, } \frac{\partial\epsilon}{\partial K} = 1$$

The approximated adaptation laws for parameters were given by

Proportional term as,

$$K_P = \left(\frac{s}{a_0 s^2 + a_{M1} s + a_{M2}}\right) e * \left(\frac{-\gamma_p}{s}\right) \epsilon \qquad (12)$$

Integral term as,

$$K_I = \left(\frac{1}{a_0 s^2 + a_{M1} s + a_{M2}}\right) e * \left(\frac{-\gamma_i}{s}\right) \epsilon \qquad (13)$$

Derivative term as,

$$K_d = \left(\frac{s^2}{a_0 s^2 + a_{M1} s + a_{M2}}\right) e * \left(\frac{-\gamma_d}{s}\right) \epsilon \qquad (14)$$

With respect to time the modification in PID controller parameters were observed by the above equations. The reference model was defined using second order transfer function with the assumption of settling time of 10 secs, maximum overshoot = 5% and finally with 2 seconds rise time. The model was finally given as

$$G_{mdl}(s) = \frac{0.706}{s^2 + 0.81s + 0.706}$$

with, $a_{M1} = 0.81$, $a_{M2} = 0.7056$ and $a_0 = 1$

6. Fuzzy Model Reference Adaptive PID Controller

Oscillations at certain period and long duration to implement adaptation were the main drawback of MRAC. In the above problem the adaptation time can be lowered by including fuzzy intelligent system with the MRAC resulting to fuzzy based modified MRAC [7-9] for shell and tube heat exchanger process. The general schematic view of fuzzy based model reference adaptive mechanism is shown in Fig 3. In MRAC the desired closed loop response and to track the response of model by the plant the parameter of controller were adjusted without considering the variation of the plant parameters. In FMRAC plant parameter variations are changed by the estimation of controller parameters

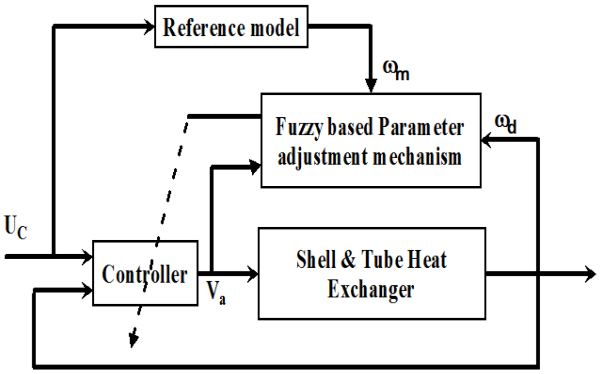

Fig 3. Structure of Fuzzy Model Reference Adaptive Controller.

The implemented fuzzy logic[11-14] includes error denoted by 'e' as one input variable and change in error 'ce' as another input variable for its two input parameter with inflow rate of cold water as output variable Δu. The input and output membership functions were selected as triangular functions with universe of discourse for input as [1 2] and universe of discourse for output as [0 0.02] is shown in Fig 4, Fig 5 and Fig 6. The rule base framed for shell and tube heat exchanger is tabulized in Table 4.

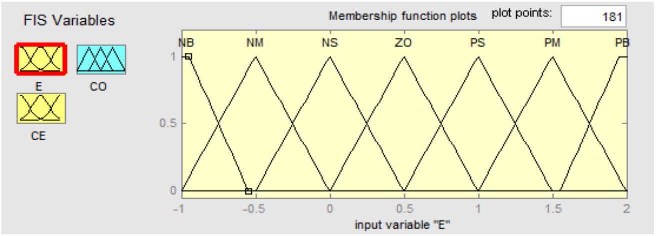

Fig 4 Membership function for error

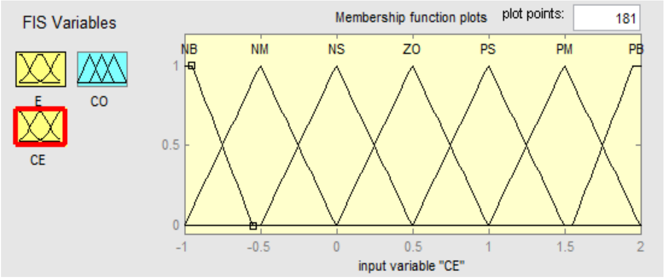

Fig 5 Membership function for change in error

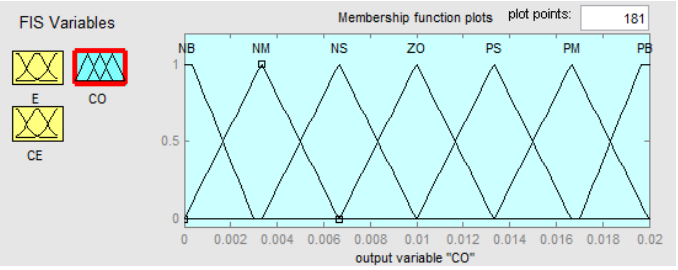

Fig 6 Membership function for controller output.

Table.4

Rules associative in fuzzy logic controller

ce e	GN	N	SN	ZE	SP	P	GP
GN	GN	GN	N	SN	N	N	ZE
N	GN	SN	SN	SN	N	ZE	SP
SN	GN	SN	N	ZE	SP	SP	P
ZE	SN	SN	N	ZE	SP	SP	P
SP	SN	ZE	SP	SP	SP	P	GP
P	ZE	ZE	SP	SP	P	GP	GP
GP	ZE	SP	SP	SP	GP	GP	GP

7. ANFIS Model Reference Adaptive PID Controller

Adaptive neuro fuzzy inference system (ANFIS) incorporates a fuzzy inference system by making use of the input/output data set presented to it. The membership functions of the fuzzy logic inference system is dynamically altered by using LSE along with back propagation algorithm that makes the fuzzy system to study from the data set. The schematic Takagi-Sugino based ANFIS architecture is given in the Fig 7. The parameters that are learnt are shown by square nodes and fixed ones are mentioned by circular nodes [15-17].

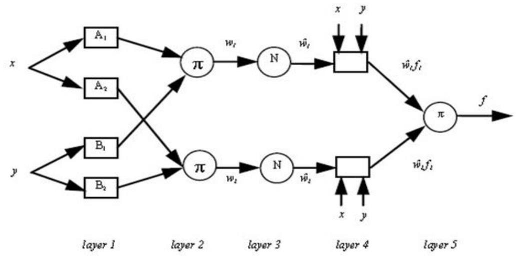

Fig 7. Takagi-sugeno system with ANFIS architecture

ANFIS has rules defined in the form:

For x is A1 and when y is B1 THEN output is p1x+q1y+r1
for x is A2 and when y is B2 THEN output is p2x + q2y + r2

ANFIS - MRAC PID control of shell and tube heat exchanger is shown in Fig 8.

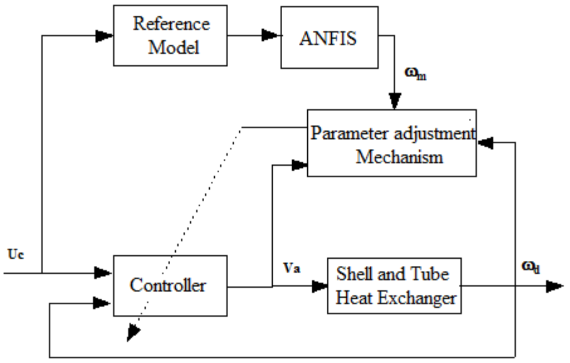

Fig 8. ANFIS based Model Reference Adaptive Controller schematic diagram

8. Results and Discussion

Shell and tube heat exchanger is controlled by PID values generated by ANFIS based MRAC at simulation level. The hot water temperature is maintained initially at a steady state value of 48°C.and the response of closed loop system is observed for step size of +2 in the temperature of outlet hot water. The same is observed with the other strategies like PID, MRAC and FMRAC and the responses are given in Fig 9 and its controller output in Fig 10. Results significantly shows ANFIS based MRAC-PID controller performance efficient than the control modes compared.

Robustness test for ANFIS based MRAC-PID controller, is carried out with hot water outlet temperature of 52°C. and compared with other control modes are plotted in Fig 11 and its controller output are presented in Fig 12. It is observed that ANFIS based MRAC-PID gives superior performance than the MRAC -PID and ZN based PID controller.

The results of STHE response with real time implementation of conventional PID controller for controlling hot water temperature at a constant hot water flow rate of 0.0282 LPS for set point temperature of 46°C along with its cold water flow rate as manipulated variable is shown in Fig 13. STHE response with real time implementation of ANFIS MRAC controller in controlling the hot water temperature at a set point of 46°C along with its cold water flow rate is as shown in figure 14. The real time response also proves the supremacy of ANFIS controller with the conventional controller.

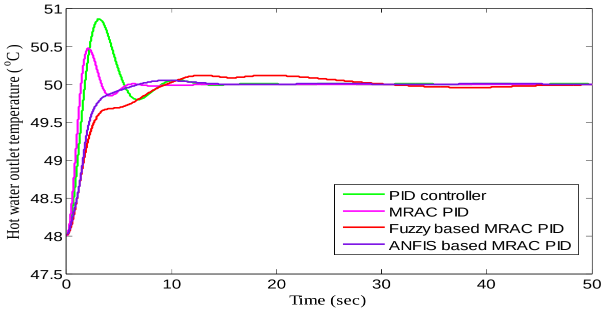

Fig 9 Shell and tube heat exchanger servo response for setpoint= 50^{o} C.

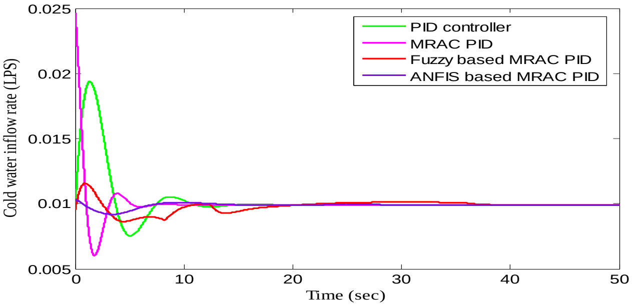

Fig 10 shell and tube heat exchanger controller response for setpoint = 50^{o} C.

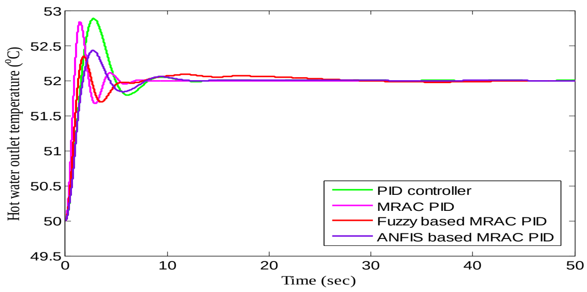

Fig 11. Shell and tube heat exchanger servo response for setpoint = 52 ° C.

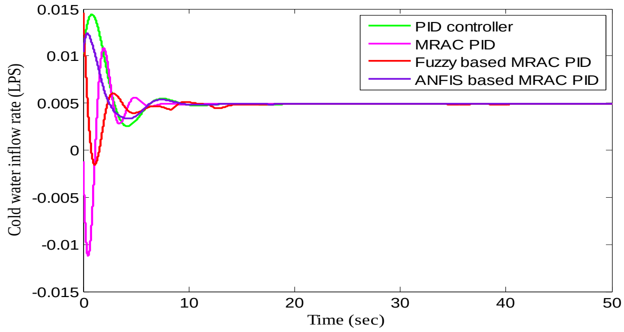

Fig 12 Shell and tube heat exchanger controller response for setpoint = 52 ° C.

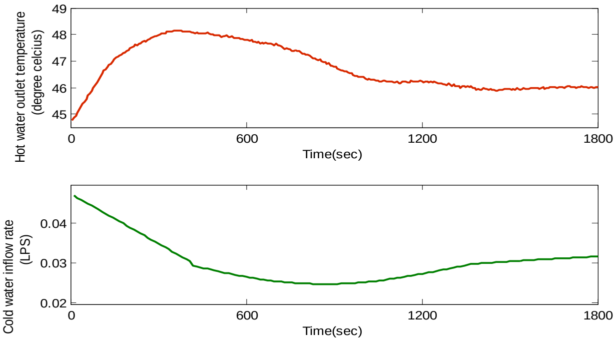

Fig 13 Experimental real time servo response of shell and tube heat exchanger at 46 ° C with PID controller.

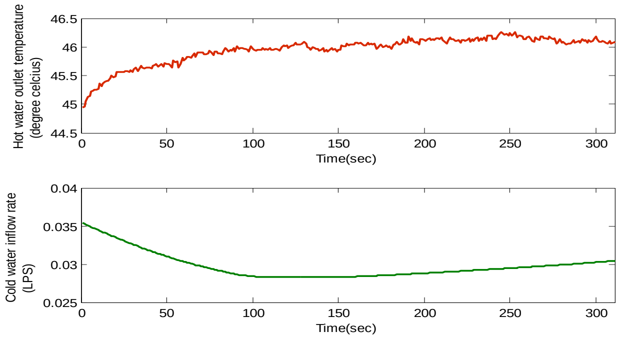

Fig 14 Experimental servo response of shell and tube heat exchanger at 46 ° C with ANFIS based MRAC-PID controller.

9. Conclusion

In this paper ANFIS MRAC based PID controller approach is newly designed and implemented. The control mechanism is well accepted by the non linear system. The ANFIS MRAC PID is developed and tested with the model derived for the shell and tube heat exchanger. The proposed controller performance is compared with the other controllers discussed. Both the simulation and experimental results proves the proposed control strategy is efficient for the process.

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