Controller Design for Temperature Control of MISO Water Tank System: Simulation Studies

Vishal Vishnoi, Dr. B. R. Ambedkar National Institute of Technology, Jalandhar, India
Sheela Tiwari, Dr. B. R. Ambedkar National Institute of Technology, Jalandhar, India
Rajesh Kumar Singla, Dr. B. R. Ambedkar National Institute of Technology, Jalandhar, India

ABSTRACT

This article introduces the design of split range control and fuzzy logic control for temperature control of the MISO (multiple input single output) water tank scheme. A multiple input single output (MISO) system is considered for the proposed work as most of the practical systems comprise numerous MISO systems. Investigations are conducted on the impact of control parameters, system dynamics, and process disturbances. From the simulation outcomes, it is clearly inferred that the fuzzy logic controller outperformed split range control over all parameters.

KEYWORDS

Fuzzy Logic Controller, Mixing Process, Split Range Control, Temperature Control

INTRODUCTION

Normally, process engineers are confronted with the problem of selection of controller for different control loops. Hence, designing and implementation of controller in process control plays a vital role. PID mode is the most commonly used mode (Ang, K. H. et al. 2005; Dreinhoefer, L.H., 1988) due to its low cost design and simplicity. However, it suffers from inherent problems of disturbance rejection, dead time associated with the process and instability. In order to improve the performance of PID controller, split range strategy was introduced (Eckman, D., 1945; Fink, E. D., 1945). This strategy involves use of more than one manipulated variables leading to the same effect on the controlled output. Split range strategy is widely used in process control. A case study of designing of split range control strategy for controlling the room temperature has been reported (Reyes-Lúa, A. et al., 2019). Mahitthimahawong S. et al. (2016) proposed application of split range control for heat exchanger networks. Mathematical modelling of heat exchanger networks was done in state space domain and performance of split range control was much better than conventional PI controller on the basis of stability analysis and utility cost.

Advances in artificial intelligence encouraged process engineers to use it in process control. Application of fuzzy logic controller is discussed in literature (Saad Afzal et al., 2016; Vincent, E.

DOI: 10.4018/IJCINI.20211001.oa35

S., 2019). It is also widely accepted in conjunction with conventional controller (Wakabayashi C. et al., 2009; Fonseca R. et al., 2013; Chetate B. et al. 2013, Mugisha Jean Claude et al., 2015) in process control. Mugisha Jean Claude et al. (2015) presented comparison of fuzzy logic controller with conventional PID controller for temperature control of heating furnace. Fuzzy logic fared well in terms of settling time, rise time and overshoot. Chetate B.et al. (2013) proposed application of PI fuzzy logic controller to control the surge instability of compression system. It was achieved by closing the feed flow valve. It was found that fuzzy logic controller gave an improved performance of compression system as stabilizing mass flow and speed in less time as compared to PID controller. Wakabayashi C. et al. (2009) used PI fuzzy control for controlling the temperature and pressure inside a polymerization reactor. It was achieved by manipulating both cold and hot oil flow rates. As compared to simple PID controller, fuzzy based control gave better response in term of overshoot, offset and ISE (integral of square error) index. Van Schoor et al. (2013) presented fuzzy logic associated with split range control strategy for control of actuator. Results showed that fuzzy logic based controller reduced the disturbances in total mass flow rate as compared to PID controller. Fonseca R. et al. (2013) used fuzzy-PI controller along with split-range control strategy for temperature control of fermentation. It was achieved by manipulating both heating and cooling water flow rates. It was found that fuzzy logic controller gave better performance in terms of ITAE (integral of time-weighted absolute error criterion) index as compared to PID controller.

Temperature is one of the important parameter in process control and due to its inherent slow varying characteristics, it is difficult to maintain at its desired set point value. Taking into account the complication and significance of temperature control and the wide scope offered by conventional and fuzzy logic controller, the work undertaken here envisages to examine the performance of the temperature control using PID controller in split range control scheme, and fuzzy logic controller.

METHODOLOGY

Model of the mixing process of two different water flows in water tank system is considered. This model is implemented in simulation model designed in MATLAB and tested with different controllers under various conditions. This section is discussed process description and various types of control methods.

Process Description

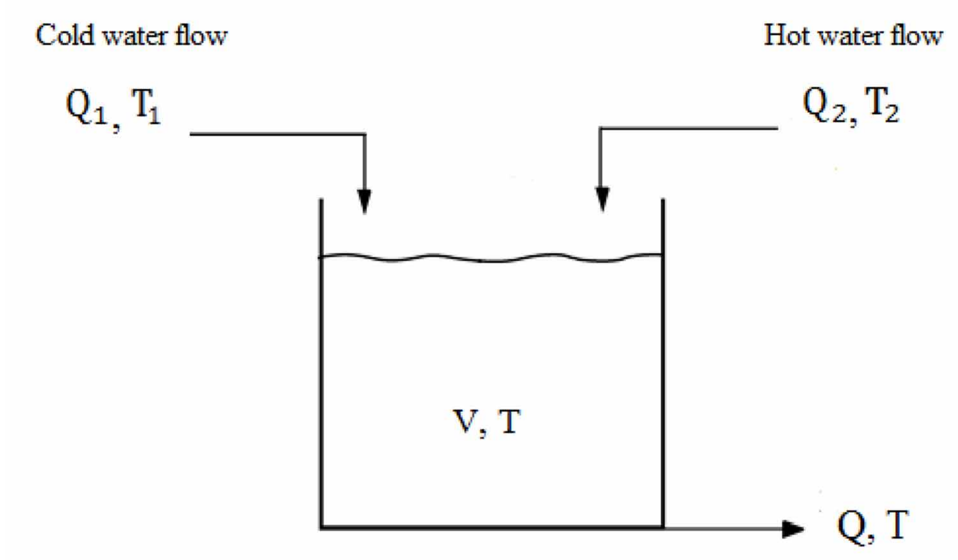
A mixing process is designed comprising of two inputs namely, cold water (flow rate Q_1, temperature T_1) and hot water (flow rate Q_2, temperature T_2). Both the constituents are mixed thoroughly and water is discharged from the outlet (flow rate Q, temperature T). The schematic diagram of mixing process of two different flows in water tank system is depicted in Figure 1.

Mathematical modelling of the process is done using mass balance equation and energy balance equation (Nagy, Z. K., 2007). The assumptions for the development of model are as follows:

- Volume of water tank is constant.
- Input flow rate is equal to output flow rate i.e. $Q = Q_1 + Q_2$.
- Density and heat capacity of water are constant.
- Perfect mixing.

On the basis of mass balance equation and energy balance equation, derived differential equation can be written as follows:

Figure 1. Mixing process of two different water flows in water tank system



$$V\frac{d\left(T\right)}{dt} = Q_1 T_1 + Q_2 T_2 - QT \; .... \tag{1}$$

General solution of Eq. (1):

$$T = T_{\infty} * \left(1 - e^{-\frac{t}{\tau}}\right) + T_0 * e^{-\frac{t}{\tau}} \; .... \tag{2}$$

Where, τ is time constant of water tank, T_0 is temperature of water at the starting of measurement and T_{∞} is temperature after the measurement of transient characteristics can be calculated as follows:

$$\tau = \frac{V}{Q_1 + Q_2}, \; .... \tag{3}$$

$$T_0 = \frac{Q_1 T_1 + Q_2 T_2}{Q_1 + Q_2}, \text{ when } t = 0, \; .... \tag{4}$$

$$T_{\infty} = \frac{Q_1 T_1 + Q_2 T_2}{Q_1 + Q_2}, \text{ when } t > 0, \; .... \tag{5}$$

For the simulation purposes, T_1 and T_2 are maintained at 20°C and 35°C respectively. Q_1 and Q_2 are varied from 0.0115 litre/sec. to 0.1 litre/sec. The operating range of T is between from 22.5°C to 32.5°C corresponding to flow rates between 0.015 litre/sec. (corresponds to 30% of valve stem position) and 0.075 litre/sec. (corresponds to 75% of valve stem position). Volume of the tank is taken as 30 litre.

Control Methods

To control the temperature of mixing process, necessity of closed loop control is important which can be done by controller. Control methods such as PID controller in conventional scheme, PID controller in split range strategy and fuzzy logic controller were considered for achieving the desired goal.

PID Controller in Conventional Scheme

The equation of PID controller with combined action is given by

$$u(t) = K_p e(t) + K_i \int_0^t e(t)\,dt + K_d \frac{de(t)}{dt} \ldots. \quad (6)$$

where,

u(t)- control signal in time domain,
Kp - proportional coefficient, a tuning parameter,
Ki - integral coefficient, a tuning parameter,
Kd - derivative coefficient, a tuning parameter,
e(t)- error signal in time domain

Initially, PID controller was tuned using Ziegler-Nichols tuning method (Bequette, B.W., 2003). However, the conventional PID control scheme was found to be inadequate in terms of steady state error which motivated to investigate performance of split range strategy for the same.

PID Controller in Split Range Strategy

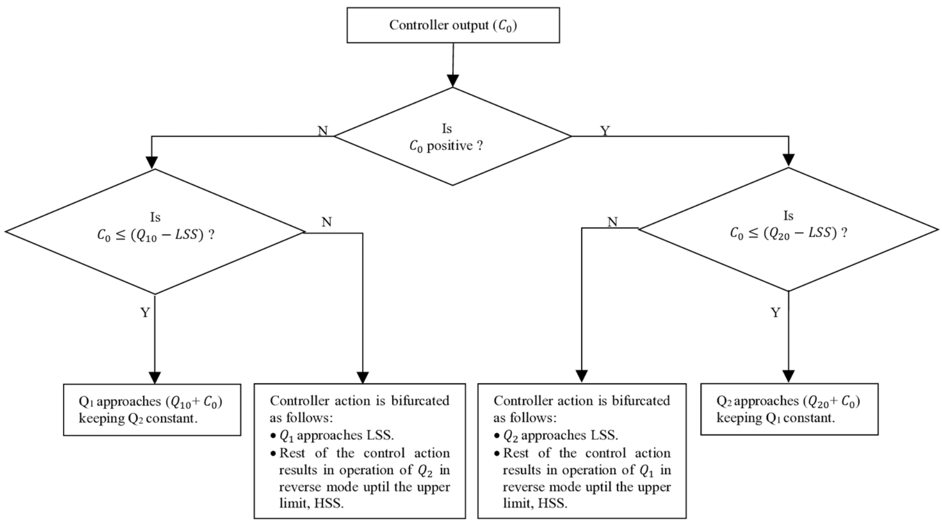
The approach of the split range adopted in this work was different from that of the normal split range strategy of dividing the whole range into two equal halves (0% to 50% and 50% to 100%). Here the strategy to divide the controller output (C_0) range depends on the initial steady state flow rates of input streams (Q_{10} and Q_{20}), lower saturation state (LSS) and higher saturation state (HSS) as depicted in Figure 2. Dividing the complete range into two equal halves does not lead to desirable results always as LSS (lower steady state) is reached well before the lower limit of the first half range. Hence, it is thought to decide the range depending on the present operating condition of the process. So that, LSS and HSS (higher steady state) corresponds to lower limit of first half and upper limit of second half respectively.

The behavior of split range strategy can be analysed by the plot of action of two valves taken as cold water valve V_1 and hot water valve V_2 corresponding to input streams Q_1 and Q_2 respectively with respect to deviation in flows (d) shown in Figure 3.

Plot of action of two valves can be understood by Tables 1(a) and 1(b) as follows:

It was observed that the latter strategy as depicted in Figure 2, gave much better results as compared to the former strategy of split range as well as the conventional PID controller scheme in terms of steady state error.

Figure 2. Flow chart of split range configuration of controller output



Fuzzy Logic Controller

In previous section, PID controller in split range strategy was used where, only one manipulated variable (Q_1 or Q_2) was used at a time. It gave better response as compared to the conventional PID controller on the basis of steady state error. In order to further improve the performance of the system in terms of settling time, it was decided to use two manipulated variables (Q_1 and Q_2) simultaneously. Due to the inherent ability of fuzzy logic controller to use human expert knowledge in an efficient manner, it was decided to investigate its performance over the conventional split range control by varying both the manipulated variables. The fuzzy logic controller was developed using simulated data of the system employing PID controller in split range scheme for the different conditions. In this work, Mamdani based fuzzy inference system (Mamdani, E. H., & Assilian, S., 1975) was used due

Figure 3. Plot of action of two valves V_1 and V_2

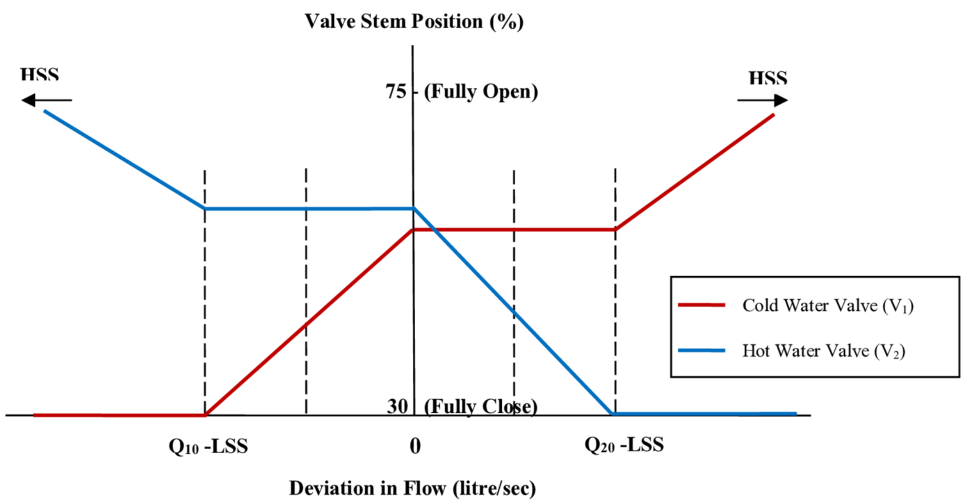


Table 1(a). Action of valves V_1 and V_2 when $d < 0$

Deviation in flow (d)	Action of valves	
	V_1	V_2
$d = 0$	No change	No change
$(Q_{10} - LSS) < d < 0$	↓	No change
$d = (Q_{10} - LSS)$	LSS	No change
$d > (Q_{10} - LSS)$	LSS	↑ and approaches HSS

Table 1(b). Action of valves V_1 and V_2 when $d > 0$

Deviation in flow (d)	Action of valves	
	V_1	V_2
$d = 0$	No change	No change
$0 < d < (Q_{20}\text{-LSS})$	No change	↓
$d = (Q_{20}\text{-LSS})$	No change	LSS
$d > (Q_{20}\text{-LSS})$	↑ and approaches HSS	LSS

to its effectiveness in capturing the human expert knowledge and a comparatively lesser number of parameters required to be determined as compared to other fuzzy inference systems such as Takagi-Sugeno fuzzy inference system (Takagi, T., & Sugeno, M., 1985), etc.

Input variables for fuzzy logic controller were considered as error (e) and change in error (Δ e). As it is inherently known that error in conjunction with change in error gives more accurate and speedy results rather than using error alone. The range for error and change in error were taken as [-10 10] and [-0.018 0.005] respectively. The selected error range corresponds to the range of temperatures (22.5°C to 32.5°C) in the working range of flow rates. Regarding to Δ e, it was found that negative Δ e implies a decrease in error with time in both the directions. As the temperature of the system approaches the set point, it overshoots the set point value resulting in a positive value of Δ e. Consequently, the controller action was initiated to restrict the Δ e at a minimum possible value. Therefore, positive value of the Δ e was observed to be much less as compared to the value on the negative side. Output variables were taken as deviation in flow rates Q_1 and Q_2, with discourse universe of [-0.06 0.06] and [-0.06 0.06] respectively as they correspond to maximum possible deviation in working range that varies from 0.015 litre/sec. to 0.075 litre/sec. Choice of membership function was influenced by the variation in temperature with respect to deviation in flow rates resulting in the selection of triangular membership functions for both input and output variables.

Table 2. Labels for defining the membership function of inputs and outputs

Error	Change in error	Deviation in flow rates Q_1 and Q_2
VVL (very very large)	NVL (negative very large)	NH (negative high)
VL (very large)	NL (negative large)	NM (negative medium)
L (large)	NM (negative medium)	NS (negative small)
ML (medium large)	NS (negative small)	Z (zero)
Z (zero)	Z (zero)	PS (positive small)
MH (medium high)	PS (positive small)	PM (positive medium)
H (high)		PH (positive high)
VH (very high)		
VVH (very very high)		

Error and change in error were classified into nine and seven categories respectively. Output variables were classified into seven categories each as shown in Table 2.

This resulted in the formation of 54 rules of fuzzy inference system discussed as follows: For all the values of change in error, and error ranging from L to VVL, $Q_1$and Q_2 are positive high (PH) and negative high (NH) respectively. Similarly, for all the values of change in error, and error ranging from H to VVH, $Q_1$and Q_2 are negative (NH) and positive high (PH) respectively. Other combination of remaining 18 rules are depicted in Table 3.

Output signals of fuzzy logic controller can be calculated by knowledge of membership functions and rule base. Controller outputs (C_0) also depends on the initial steady state flow rates of input streams (Q_{10} and Q_{20}), lower saturation state (LSS) and higher saturation state (HSS) as depicted in Figure 4.

The behavior of deviation in flow rates can be analysed by the plot of action of two valves taken as valves V_1 and V_2corresponding to deviation in flows (d) as shown in Figure 5. It indicates that both the valves were manipulated simultaneously when the set point was increased or decreased with respect to the initial temperature.

Plot of action of two valves with respect to deviation in flows rates can be understood by Table 4 as follows:

RESULTS AND DISCUSSION

In this study, PID controller (in split range scheme) and fuzzy logic controller were used for controlling the temperature of process. Performance of both the control schemes for different set points within the working range of temperature (22.5°C to 32.5°C) were checked. Results are discussed on the basis of three criteria: effect of control parameters, effect of system dynamics and effect of disturbance.

Effect of Control Parameters

Simulation results were obtained on the basis of steady state error (e_{ss}), settling time (T_s) and performance index in terms of ISE (integral square of error). On the basis of simulation results obtained from various set points, comparative study was made for both the schemes and it was found that fuzzy logic controller gave better response as shown in Tables 5 and 6. In Table 5, 1% tolerance of settling time is taken for settling the response. The steady state error was found to be zero for all cases in Table 5.

Table 3. Fuzzy rules for temperature control

Rule	Antecedent part			Consequent part		
1	If e is ML	and	Δ e is NVL	then	Q_1 is PM	Q_2 is NH
2	If e is ML	and	Δ e is NL	then	Q_1 is PM	$Q_2$is NM
3	If e is ML	and	Δ e is NM	then	Q_1 is PM	$Q_2$is NM
4	If e is ML	and	Δ e is NS	then	Q_1 is PM	$Q_2$is NM
5	If e is ML	and	Δ e is Z	then	Q_1 is PM	$Q_2$is NM
6	If e is ML	and	Δ e is PS	then	Q_1 is PS	$Q_2$is NM
7	If e is Z	and	Δ e is NVL	then	Q_1 is Z	$Q_2$is NS
8	If e is Z	and	Δ e is NL	then	Q_1 is Z	$Q_2$is NS
9	If e is Z	and	Δ e is NM	then	Q_1 is Z	$Q_2$is NS
10	If e is Z	and	Δ e is NS	then	Q_1 is Z	$Q_2$is NS
11	If e is Z	and	Δ e is Z	then	Q_1 is Z	$Q_2$is NS
12	If e is Z	and	Δ e is PS	then	Q_1 is NS	$Q_2$is Z
13	If e is MH	and	Δ e is NVL	then	Q_1 is NM	$Q_2$is PS
14	If e is MH	and	e is NL	then	Q_1 is NM	$Q_2$is PM
15	If e is MH	and	Δ e is NM	then	Q_1 is NM	$Q_2$is PM
16	If e is MH	and	Δ e is NS	then	Q_1 is NM	$Q_2$is PM
17	If e is MH	and	Δ e is Z	then	Q_1 is NH	$Q_2$is PM
18	If e is MH	and	Δ e is PS	then	Q_1 is NH	$Q_2$is PM

Effect of System Dynamics

Initially, performance of system was checked using both the control schemes with valve (without delay), then performance of system equipped with valves (delay of 0.25 second and 0.5 second) was investigated for both the control schemes. It was found that increase in delay increased the settling time for both the cases. It is pertinent to mention that fuzzy logic controller reduced the settling time by significant amount as compared to PID controller (in split range scheme).

Effect of Disturbances

The performance of the system in the presence of disturbance (impulse) was checked and it was found that fuzzy logic controller fared better in comparison to PID controller in term of settling time.

Figure 4. Flow chart for controller output of fuzzy logic controller

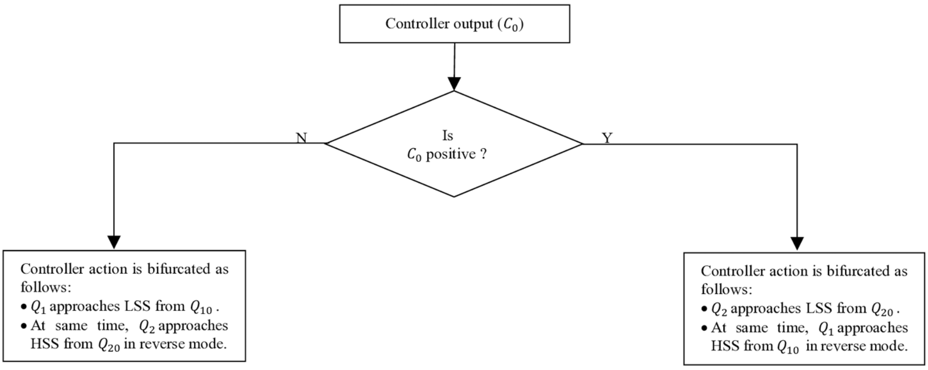


Figure 5. Plot of action of two valves V_1 and V_2 (behavior of deviation in flow rates)

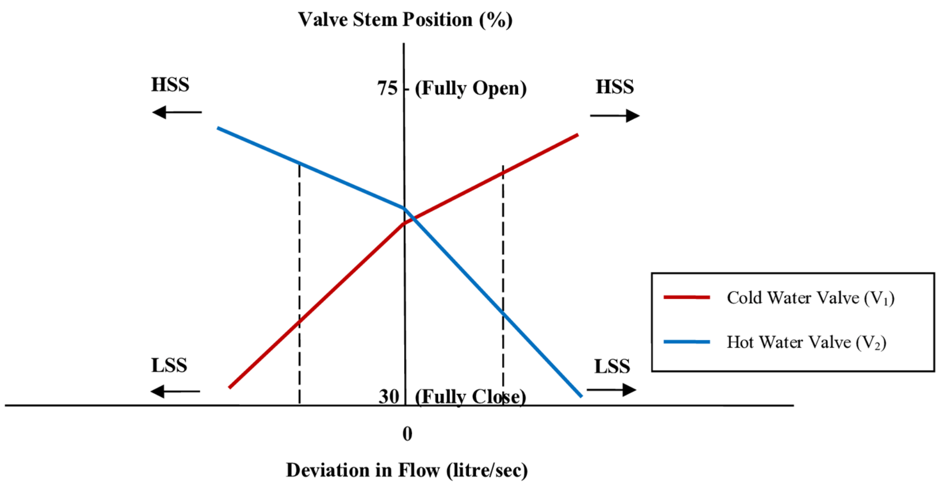


Table 4. Action of valves V_1 and V_2 with respect to deviation in flows rates

Deviation in flow (d)	Action of valves	
	V_1	V_2
$d = 0$	No change	↑ No change
$d < 0$	↓ and approaches LSS	and approaches HSS
$d > 0$	↑ and approaches HSS	↓ and approaches LSS

Table 5. Comparative study of transient response of controllers

Set points (°C)	Error	Valve (without delay)		Valve (delay of 0.25 second)		Valve (delay of 0.5 second)	
		PID controller (in split range scheme)	Fuzzy logic controller	PID controller (in split range scheme)	Fuzzy logic controller	PID controller (in split range scheme)	Fuzzy logic controller
		Ts (sec.)	Ts (sec.)	Ts (sec.)	Ts (sec.)	Ts (sec.)	Ts (sec.)
25	+3	565	343	662	400	799	490
	+2	249	232	305	257	385	328
	-1	628	500	736	566	875	673
	-2	4496	1814	5093	1838	5836	2215
27.5	+3	1100	388	1311	491	1586	621
	+2	595	237	698	267	838	338
	-1	267	207	314	216	367	240
	-2	601	443	704	481	846	528
29	+3	3563	2517	4250	3182	5117	4053
	+2	1653	594	1903	691	2199	806
	-1	196	155	228	179	267	201
	-2	418	324	492	360	588	415

Table 6. Comparative study of performance index (ISE) for both the control schemes

Set points (°C)	Error	Valve (without delay)		Valve (delay of 0.25 second)		Valve (delay of 0.5 second)	
		PID controller (in split range scheme)	Fuzzy logic controller	PID controller (in split range scheme)	Fuzzy logic controller	PID controller (in split range scheme)	Fuzzy logic controller
		ISE	ISE	ISE	ISE	ISE	ISE
25	+2	286.1	238.4	352.4	290.0	438.7	364.4
	-1	124.5	83.6	149.3	85.7	181.7	101.1
27.5	+2	405.9	254.8	505.5	316.6	634.4	396.2
	-1	95.5	66.8	107.6	69.0	123.7	72.3
29	+2	752.1	486.9	889.2	538.0	1063.9	604.0
	-1	77.9	65.7	87.4	69.3	100.1	73.6

The above discussion clearly shows that the fuzzy logic controller provided an improved control under various conditions as compared to PID controller in split range scheme.

CONCLUSION

This work highlighted the comparative study of fuzzy logic controller with conventional split range scheme for temperature control of a mixing process. Simulation results clearly established a superior performance of fuzzy logic controller over the entire operating range of temperature in terms of setting time and ISE index as compared to conventional PID controller in split range scheme. Fuzzy logic controller also nullified the effect of system dynamics. It also demonstrated an improved performance in the presence of disturbance. However, due to inherent time consuming nature of fuzzy logic controller, investigation is further required for replacement of existing PID controller with fuzzy logic controller in present industrial scenario.

REFERENCES

Ang, K. H., Chong, G., & Li, Y. (2005). PID control system analysis, design, and technology. *IEEE Transactions on Control Systems Technology*, *13*(4), 559–576. doi:10.1109/TCST.2005.847331

Bequette, B. W. (2003). *Process control: modeling, design, and simulation*. Prentice Hall Professional.

Chetate, B., Zamoum, R., Fegriche, A., & Boumdin, M. (2013). PID and novel approach of PI fuzzy logic controllers for active surge in centrifugal compressor. *Arabian Journal for Science and Engineering*, *38*(6), 1405–1414. doi:10.1007/s13369-013-0601-6

Dreinhoefer, L. H. (1988). Controller tuning for a slow nonlinear process. *IEEE Control Systems Magazine*, *8*(2), 56–60. doi:10.1109/37.1875

Eckman, D. (1945). *Principles of industrial control*. John Wiley & Sons.

Fink, E. D. (1945). Instruments and Process Control. Delmar Publishers, Inc.

Fonseca, R. R., Schmitz, J. E., Fileti, A. M. F., & da Silva, F. V. (2013). A fuzzy–split range control system applied to a fermentation process. *Bioresource Technology*, *142*, 475–482. doi:10.1016/j.biortech.2013.05.083 PMID:23759431

Mahitthimahawong, S., Tarapoom, N., Skogestad, S., Srinophakun, T., & Lertbumrungsuk, V. (2016). Application of Passivity Concept for Split Range Control of Heat Exchanger Networks. *Journal of Chemical Engineering & Process Technology*, *7*(1), 274.

Mamdani, E. H., & Assilian, S. (1975). An experiment in linguistic synthesis with a fuzzy logic controller. *International Journal of Man-Machine Studies*, *7*(1), 1–13. doi:10.1016/S0020-7373(75)80002-2

Mugisha, J. C., Munyazikwiye, B., & Karími, H. R. (2015). Design of temperature control system using conventional PID and Intelligent Fuzzy Logic controller. In *Fuzzy Theory and Its Applications (iFUZZY), 2015 International Conference on*, (pp. 50-55). IEEE.

Nagy, Z. K. (2007). Model based control of a yeast fermentation bioreactor using optimally designed artificial neural networks. *Chemical Engineering Journal*, *127*(1-3), 95–109. doi:10.1016/j.cej.2006.10.015

Reyes-Lúa, A., Zotică, C., Forsman, K., & Skogestad, S. (2019). Systematic Design of Split Range Controllers. *IFAC-PapersOnLine*, *52*(1), 898–903. doi:10.1016/j.ifacol.2019.06.176

Saad Afzal, M. J., Waris, A., Butt, S. I., & Mufti, G. (2016). Fuzzy logic controller for boiler temperature control using labview and matlab. *International Journal of Control and Automation*, *9*(9), 89–104. doi:10.14257/ijca.2016.9.9.10

Takagi, T., & Sugeno, M. (1985). Fuzzy identification of systems and its application to modeling and control. *IEEE Transactions on Systems, Man, and Cybernetics*, *15*(1), 116–132. doi:10.1109/TSMC.1985.6313399

Van Schoor, G., Breed, D. G., & Du Rand, C. P. (2013). Fuzzy logic controller with neural network signal predictors for complex split-range control of a hybrid actuator. *Sensors and Actuators. A, Physical*, *199*, 216–226. doi:10.1016/j.sna.2013.05.017

Vincent, E. S., Chukwudumebi, N., Oluwaseun, A. T., George, O. E., Edward, R. F. A., & Chukwudi, C. V. (2019). Application of Fuzzy Logic Temperature Controller for Water Bottle Industry. *Computer Engineering and Intelligent Systems*, *10*(2), 16–22.

Wakabayashi, C., Embiruçu, M., Fontes, C., & Kalid, R. (2009). Fuzzy control of a nylon polymerization semi-batch reactor. *Fuzzy Sets and Systems*, *160*(4), 537–553. doi:10.1016/j.fss.2008.08.009

Vishal Vishnoi is pursuing Ph.D. in department of Instrumentation and Control Engineering at Dr. B. R. Ambedkar National Institute of Technology (NIT), Jalandhar, Punjab, India. He is completed M.E. in Electrical Instrumentation and Control Engineering from Thapar University, Patiala; B.Tech in Electronics Instrumentation & Control from Greater Noida Institute of Technology (GNIT), Greater Noida, Uttar Pradesh. Research interests are control system, process control, modelling and simulation.

Sheela Tiwari is an Associate Professor in the department of Instrumentation and Control Engineering at Dr. B. R. Ambedkar National Institute of Technology (NIT), Jalandhar, Punjab, India. She completed her B.Tech in Electrical Engineering from Thapar Institute of Engineering and Technology, Patiala; M.Tech in Instrumentation and Control Engineering from PAU Ludhiana; and Ph.D. in Instrumentation and Control Engineering from NIT Jalandhar. Her research interests are soft computing, power system operation and control.

Rajesh Kumar Singla is an Associate Professor in the department of Instrumentation and Control Engineering at Dr. B. R. Ambedkar National Institute of Technology (NIT), Jalandhar, Punjab, India. He completed his B.E. in ICE at Thapar University; M.Tech in Electrical from IIT Roorkee; and Ph.D. in Instrumentation and Control Engineering from NIT Jalandhar. His research interests are human-machine interface, rehabilitation engineering and process control. He has published numerous papers in international journals and conference proceedings.