Study of Continuous Stirred Tank Reactors Control Strategies

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ABSTRACT: Continuous Stirred Tank Reactors (CSTR) are the most important and central equipment in many chemical and biochemical industries which exhibit complex nonlinear dynamics of the second order. CSTR's nonlinear dynamics pose number of challenges to design and control. The mathematical model of the system was derived. A conventional Proportional Integral PI, Proportional Derivative PD, Proportional Integral Fuzzy Logic Controller PIFLC, and Proportional Derivative Fuzzy Logic Controller PDFLC for continuous stirred tank reactor are proposed to control the concentration of the linear CSTR. The simulation study has been conducted in MATLAB SIMULINK. The best controller has been chosen by comparing the criteria of the response such as settling time, rise time, percentage of overshoot and steady state error. From the simulation results the PD fuzzy logic controller has a better performance than other controllers.

KEYWORDS: Continuous Stirred Tank Reactor, Modelling; Nonlinear Model, PI, PD, PIFLC & PDFLC Controllers.

I.INTRODUCTION

Continuously stirred tank reactors (CSTR) are the principal compartment of several plants in the chemical industry. From the point of view of system engineering, CSTR belongs to a class of nonlinear systems in which both steady-state and dynamic behavior are nonlinear. Chemical reactor control is a demanding activity and is also one of the most important areas of study from a process control point of view. Control system innovation has gained tremendous interest in the chemical industry today [1]. The maximum efficiency of a chemical process in terms of product quality, production rate, and cost of operation can only be achieved by accurate control of operating conditions. Developing new control strategies remains an increasing field of interest and offers a way to solve problems [2].

The CSTR is a typical chemical reactor system with complex nonlinear characteristics. The system consists of two tanks as illustrated in fig 1. The concentration of the outlet flow of two chemical reactors will be forced to have a specified response. The overflow tanks are assumed to be well mixed isothermal reactors, and the density of both tanks is the same. The amounts in the two tanks can be taken to be constant due to the assumptions for the overflow tanks, and all the flows areconstant and equal. The inlet flow is assumed to be constant. The second tank concentration is needed based on the concentration in the first tank [3,4].

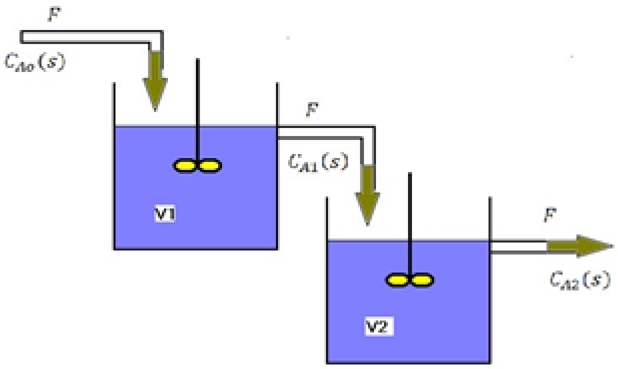


Fig 1. CSTR system

II.MATHEMATICAL MODEL

The concentration of the outlet flow of two chemical reactors will be forced to have a specified response in this project Fig 1 shows our simple concentration process control. It is assumed that the overflow tanks are well-mixed isothermal reactors, and the density is the same in both tanks. Due to the assumptions for the overflow tanks, the volumes in the two tanks can be taken to be constant, and all flows are constant and equal. It is assumed that the inlet flow is constant $F=0.085m^2$/min, and $V_1=V_2=1.05m^3$. In addition, the chemical reaction is first order $-k\ C_A$with $k=0.040^{\ min\text{-}1}$.

The value of the concentration in the second tank is desired, but it depends on the concentration in the first tank. Therefore, the component balances in both tanks are formulated [2].

First Tank: $V_1 \dfrac{dC_{A1}}{dt} = F(C_{A0} - C_{A1}) - V_1 k C_{A1}$. (1)

$$V_2 \frac{dC_{A2}}{dt} = F(C_{A1} - C_{A2}) - V_2 k C_{A2}. \quad (2)$$

The result is two linear ordinary differential equation, which is in general must be solved simultaneously. Note that the two equations could be combined into a single second-order differential equation; thus, the system is second order [5,6]. To find the model of the two chemical reactors, the Laplace transforms for the Eq. (1) and the Eq. (2) are obtained, noting that the initial conditions are zero.

$$sVC_{A1}(s) = F\left[C_{A0}(s) - C_{A1}(s)\right] - VkC_{A1}(s). \quad (3)$$

$$sVC_{A2}(s) = F\left[C_{A1}(s) - C_{A2}(s)\right] - VkC_{A2}(s). \quad (4)$$

The equations can be combined into one equation by eliminating CA1(s) from the second equation. First, solve for CA1(s) in equation (3). Thus,

$$C_{A1}(s) = \frac{k_P}{\tau s + 1} C_{A0}(s). \quad (5)$$

Where $\tau = \dfrac{V}{F + Vk} = 8.25\,\text{min}$, and $k_P = \dfrac{F}{F + Vk} = \sqrt{0.448}$.

$$C_{A2}(s) = \frac{k_P}{\tau s + 1} C_{A1}(s). \quad (6)$$

Therefore, $\dfrac{C_{A2}(s)}{C_{A0}(s)} = \dfrac{(k_P)^2}{(\tau s + 1)^2} = \dfrac{0.006582}{s^2 + 0.242424s + 0.014692}$. (7)

Fig (2a) shows the individual transfer functions for each tank, and fig (2b) shows the function of the whole system.

Fig. 2a The individual transfer functions for each tank.

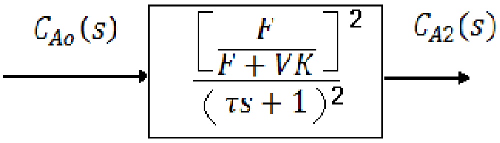


Fig. 2b The function of the whole system.

III.CONTROLLERS DESIGHN

The Simulink environment in MATLAB software was used to find the step response of the system and then to design the proposed controllers, the overall system block diagram is shown in fig 3.

$$G(s)=\frac{C_{A2}(s)}{C_{A0}(s)}=\frac{0.006582}{s^2+0.242424s+0.014692}$$

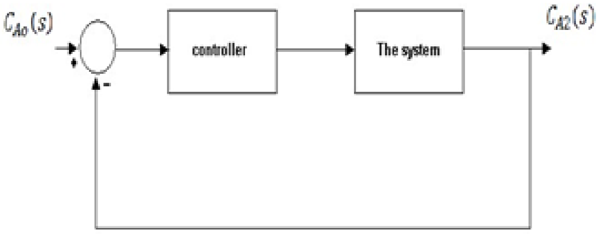


Fig. 3 The basic configuration of the close loop system.

3.1 THE SIMULATION RESPONSE OF THE UNCOMPENSATED SYSTEM:

The first response considered in this work is to investigate the close loop system response without controller which is shown in fig 4. This result indicates that the final value is 0.30943, while the desired value is 1. It is noticed that the response has high error compared with the desired value. Figures in table 1 give insight to the deviation of the uncompensated response from the desired value. This suggests the need to design a robust controller to tackle this problem which is explained in the upcoming sections.

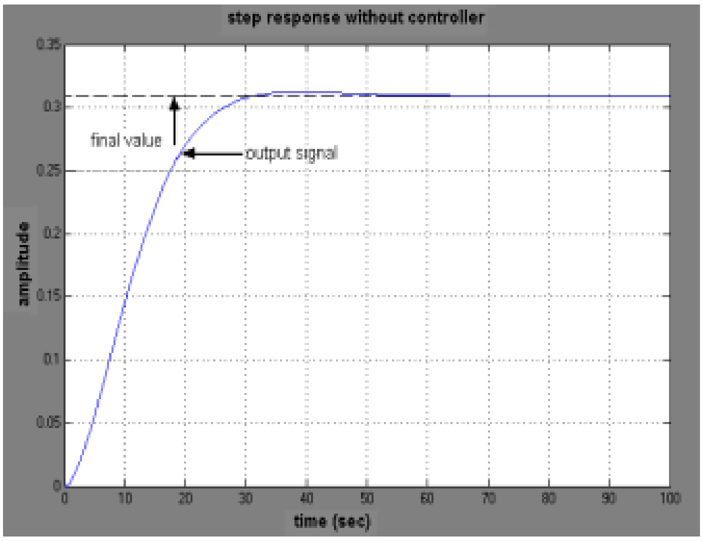


Fig. 4 Step response of the system without controller.

Table 1. Performance specification of step response without controller.

Controller	S-S Error	Overshoot	Rise time	Settlingtime
Uncompensated	69.057%	0%	17.8s	27.5s

The proportional integral derivative controller (PID) is the most popular feedback controller used in the process industries. It is a robust, easily understood controller that can provide excellent control performance despite the varied dynamic characteristics of process plant. As the name suggests, the PID algorithm consists of three basic modes, the proportional mode, the integral and the derivative modes. A proportional controller has the effect of reducing the rise time, but never eliminates the steady-state error. An integral control has the effect of eliminating the steady-state error, but it may make the transient response worse. A derivative control has the effect of increasing the stability of the system, reducing the overshoot, and improving the transient response. Proportional integral (PI) controllers are the most often type used today in industry. A control without derivative (D) mode is used when: fast response of the system is not required; large disturbances and noises are present during operation of the process and there are large transport delays in the system. Derivative mode improves stability of the system and enables increase in proportional gain and decrease in integral gain which in turn increases speed of the controller response. In view of the above, PI and PD structured controllers are considered to be investigated in the present paper.

Fuzzy logic is widely used in the real-time industrial applications and embedded systems. A typical Fuzzy Controller shown in fig 5 is a one-input-one-output controller. This structure can be modified into multi-input/multi-output fuzzy controller by adding an extra Fuzzy Membership Function (MSF) at each additional input or output. Scaling gains can be added to the inputs making the fuzzy controller act as a classical form of PD/PI controller as used in the following sections. The benefits of these gains are to re-scale the range of the universe of discourse of the MSF. These values are very important to get better control performance. In this paper, PI and PD fuzzy logic controller structured controllers are proposed for investigation to control the concentration of the linear CSTR.

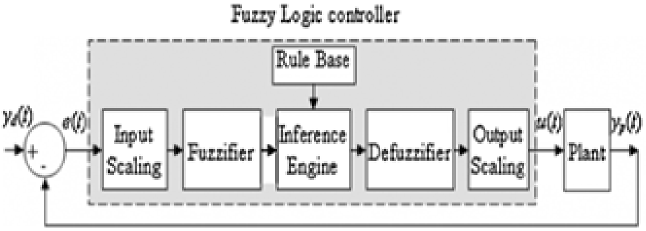


Fig. 5Typical structure of fuzzy logic controller.

3.2 PI CONTROLLER

The simulation result when the PI controller applied is shown in fig 6, the response has been improved to meet the requirement of the desired signal, the characteristics of the controlled system which given in table 2 confirm this improvement. However, the settling time and overshoot in this figure still need to be compensated.

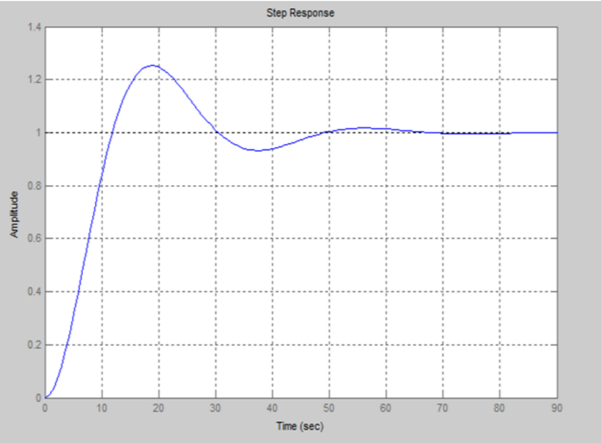


Fig. 6 Step response of the system with PI controller applied.

Table 2. Characteristics of the system when PI controller applied.

Controller	S-S Error	Overshoot	Rise time	Settling time
PI controller	0%	25.3%	8.06sec	46sec

3.3 SIMULATION DESIGN OF THE PI FUZZY LOGIC CONTROLLER PIFLC

3.3.1 FUZZY-PI CONTROLLER STRUCTURE

Structure of fuzzy-PI controller for system is shown in fig 7. The performance of the fuzzy-PI controller depends on the input and output scaling factors. Therefore, in designing an optimum fuzzy-PI controller these gains must be selected properly in order to achieve better dynamic response for the closed loop system. The desired dynamic response should have minimum settling time with a small or no overshoot and undershoot. Different conventional techniques to determine these gains are: trial and error method, Zeigler–Nichols method etc. In this paper trail and error method is employed to get the optimum values of controller gains in order to extract better dynamic performance from the fuzzy-PI controlled the system.

For the PI fuzzy logic controller the inputs error(E) and rate of change of E and the output u1 are transformed into five linguistic variables namely NB (Negative Big), NS (Negative Small), Z (Zero), PS (Positive Small) and PB (Positive Big). Triangular membership function shown in fig. 8 is used for both the inputs and the output. Number and shape of fuzzy sets.

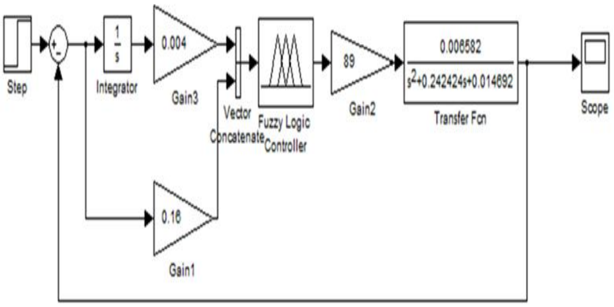


Fig. 7 Simulink block diagram of the system with PIFLC.

3.3.2 FUZZY CONTROLLER RULE BASE

Since each variable of the fuzzy controller (two inputs and one output) has 5 membership functions, 25 rules are required to generate a fuzzy output. The rule base of the fuzzy logic controller is given in Table 3 and represented in fig 9. Fuzzy rules play major role in the performance of fuzzy logic controllers and therefore, in this paper the rules are investigated extensively by studying the dynamic behavior of the system. The firing strength of the fuzzy control rules are obtained by using Mamdani interface engine.

Table 3. Fuzzyrules for the inputs and output.

E	$\dot{E}$				
	NB	**NS**	**Z**	**PS**	**PB**
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

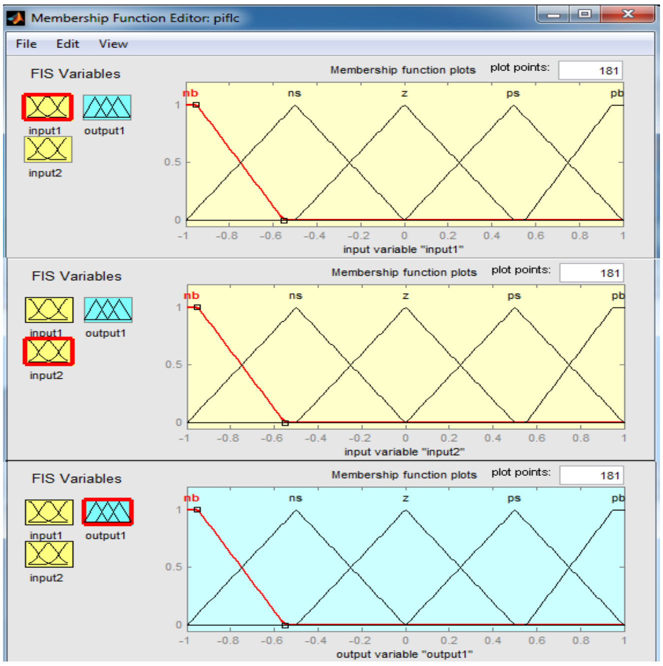
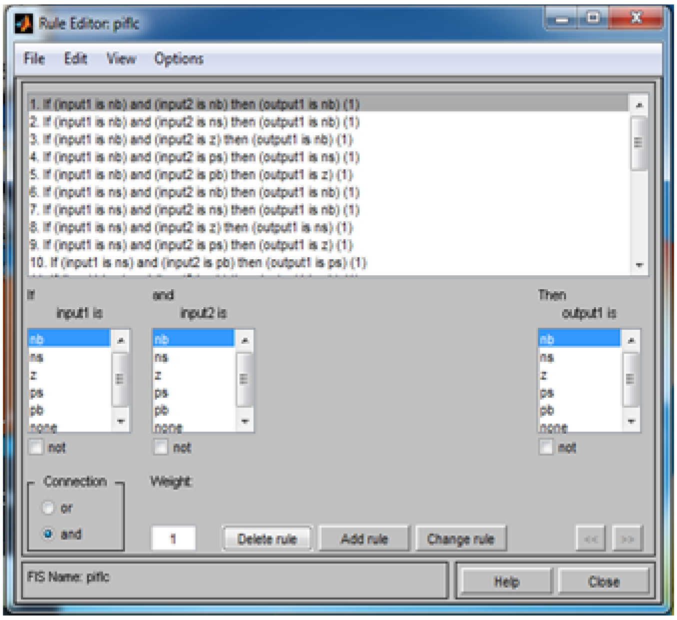


Fig.8 Membership function of the (inputs & output) of the PIFLC.



1. If (input1 is nb) and (input2 is nb) then (output1 is nb) (1)
2. If (input1 is nb) and (input2 is ns) then (output1 is nb) (1)
3. If (input1 is nb) and (input2 is z) then (output1 is nb) (1)
4. If (input1 is nb) and (input2 is ps) then (output1 is ns) (1)
5. If (input1 is nb) and (input2 is pb) then (output1 is z) (1)
6. If (input1 is ns) and (input2 is nb) then (output1 is nb) (1)
7. If (input1 is ns) and (input2 is ns) then (output1 is nb) (1)
8. If (input1 is ns) and (input2 is z) then (output1 is ns) (1)
9. If (input1 is ns) and (input2 is ps) then (output1 is z) (1)
10. If (input1 is ns) and (input2 is pb) then (output1 is ps) (1)

Fig. 9 The menu of structure of linguistic fuzzy rule base.

3.3.3 DEFUZZIFICATION

The output of the interface engine is a fuzzy value and therefore it must be converted to a real value. The process of conversion of a fuzzy value to a real value with which the physical system can deal is known as defuzzification. The very popular center of gravity method of defuzzification is used to determine the required.

3.3.4 PI FUZZY LOGIC CONTROLLER RESULTS

As fig 7 shows, two input gains are set along with one output gain, an integrator is allocated at one of the inputs, this represents the (I) factor. The response obtained from applying this approach is shown in fig 10. The main characteristics of the controller makes it favorable over the conventional PI response is provided in table 4. The improvements achieved from this proposed.

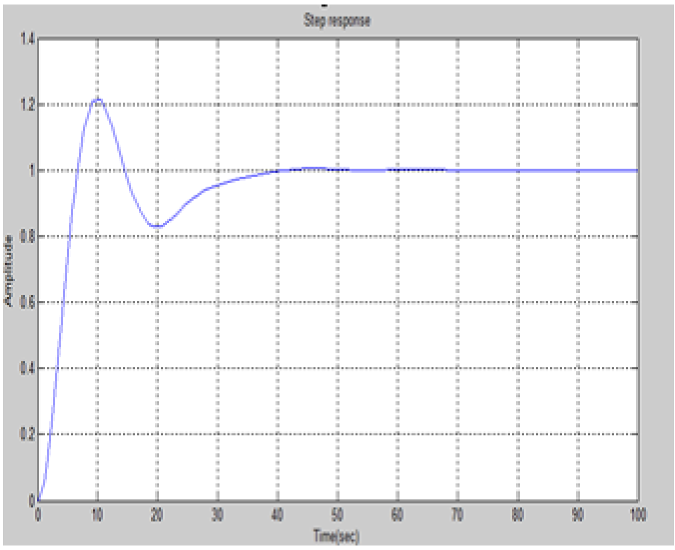


Fig. 10 Response of the system when PIFLC applied.

Table 4. Characteristics of the system when piflc applied.

Controller	S-S Error	Overshoot	Rise time	Settling time
PIFLC	0%	1.215%	4.34sec	38sec

3.4 PD CONTROLLER

It is known that when the PD is considered the I term equals to zero.The simulation result when the PD controller investigated is shown in fig 11,performanceof the system whenPD controller applied is given in table 5.The response has large steady state error, as this controller is commonly used along with the I component to make PID. As it is demonstrated, this controller does not give a desired response which makes it less recommended for this application.

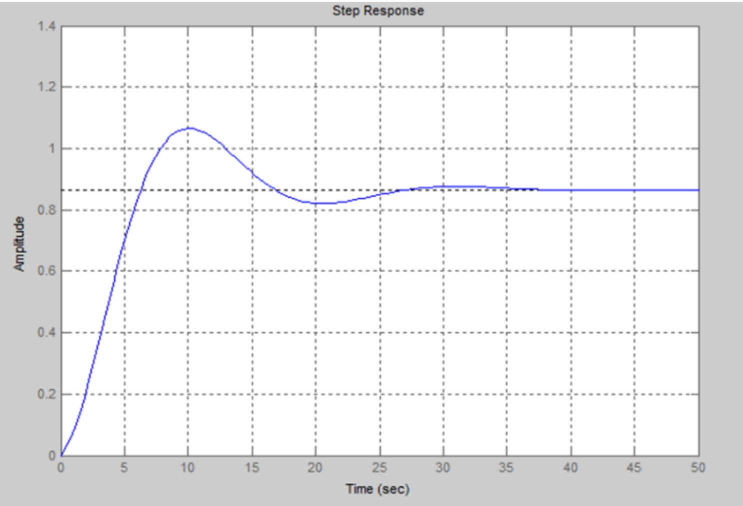


Fig. 11 Response of the system when PD controller applied.

Table 5. Characteristics of the system whenPD controller applied.

Controller	S-S Error	Overshoot	Rise time	Settling time
PD controller	13.4%	23%	4.49sec	24.9sec

3.5 DESIGN SIMULINK FOR THE SYSTEM WITH PDFLC:

The structure of the PDFLC is provided in fig 12, which the Derivative part is used instead of the Integral, this will form the PDFLC. The same fuzzy inference system(FIS) file has been used for both scenarios, which gives a real fare to make a comparison among the proposed controllers. From fig 16, it is noticeable that this approach gives the best response it all aspects, for instance; this response has zero steady state error with the fastest response without having an overshoot.

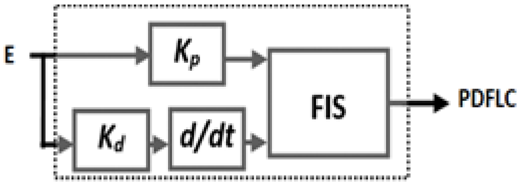


Fig. 12 Design layout of the PDFLC.

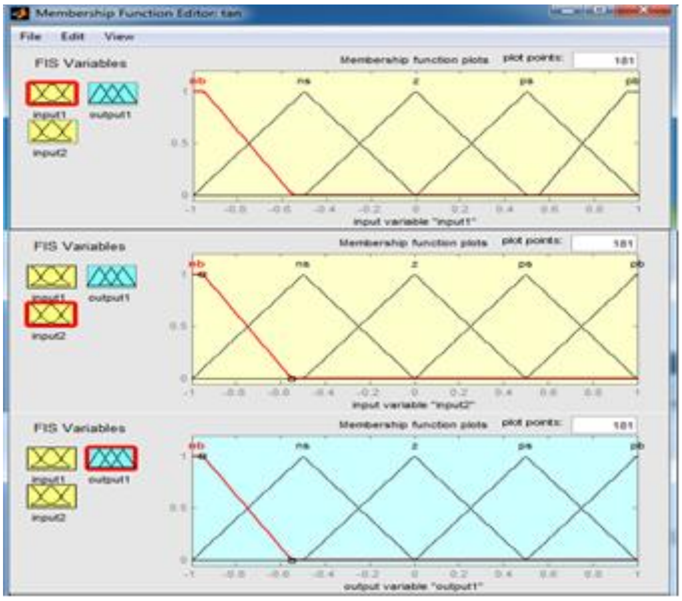
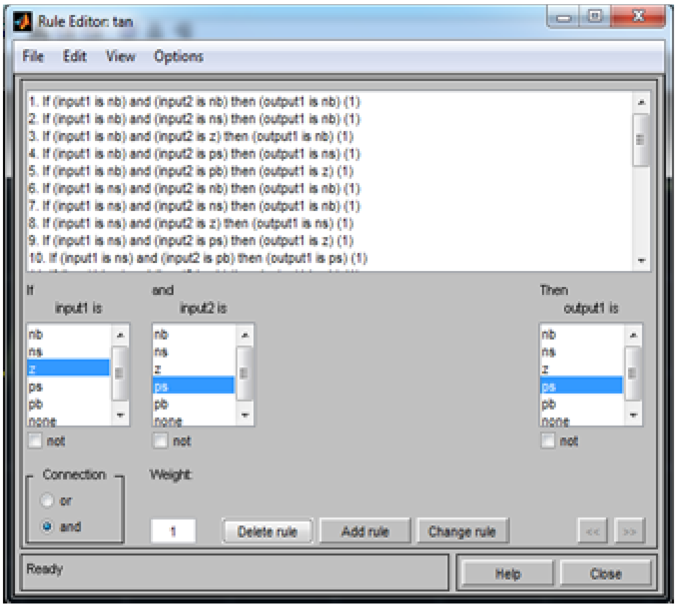


Fig. 13 The membership function of the inputs and output of the PDFLC.



1. If (input1 is nb) and (input2 is nb) then (output1 is nb) (1)
2. If (input1 is nb) and (input2 is ns) then (output1 is nb) (1)
3. If (input1 is nb) and (input2 is z) then (output1 is nb) (1)
4. If (input1 is nb) and (input2 is ps) then (output1 is ns) (1)
5. If (input1 is nb) and (input2 is pb) then (output1 is z) (1)
6. If (input1 is ns) and (input2 is nb) then (output1 is nb) (1)
7. If (input1 is ns) and (input2 is ns) then (output1 is nb) (1)
8. If (input1 is ns) and (input2 is z) then (output1 is ns) (1)
9. If (input1 is ns) and (input2 is ps) then (output1 is z) (1)
10. If (input1 is ns) and (input2 is pb) then (output1 is ps) (1)

Fig. 14 The menu structure of linguistic fuzzy rule base.

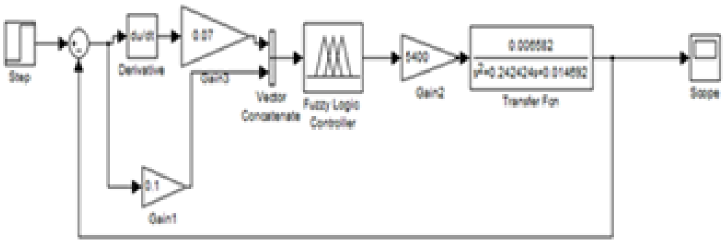


Fig. 15 Simulink block diagram of the system when PDFLC applied.

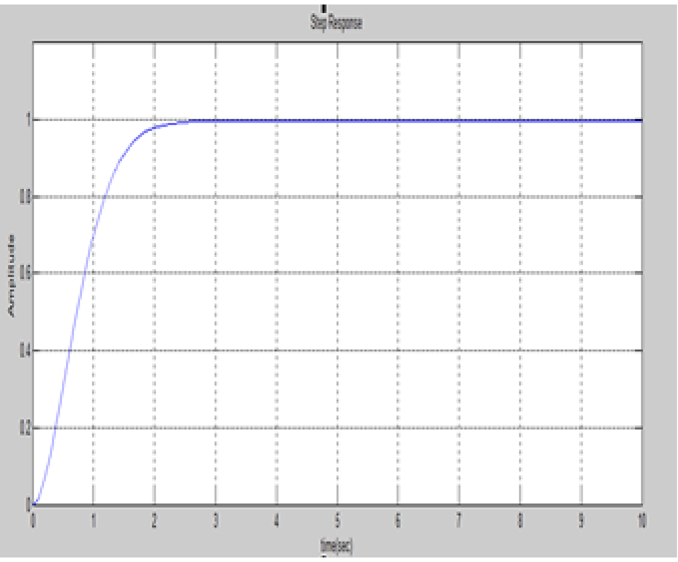


Fig. 16 Response of the system when PDFLC applied.

Table 6. The characteristics of the system when PDFLC applied.

Controller	S-S Error	Overshoot	Rise time	Settling time
PDFLC	0%	0%	1.2sec	2.6 sec

IV.COMPARISON & DISCUSSION

4.1 COMPARATIVE BETWEEN PI CONTROLLER AND PIFLC

To show the effectiveness of the proposed controllers in controlling the concentration, several competitive simulations are carried out on the system. This section gives a comparison between the (PI & PIFLC). In fig17, a step response is illustrated which gives insight for the superiority of the fuzzy logic approach over the conventional controllers especially in transient region.

4.2 COMPARATIVE BETWEEN PD AND PDFLC

Another advantage of using the fuzzy logic controllers over the classical controllers is confirmed in this part. As fig 18 explains the response of the studied system when PD and PDFLC applied, it is clear that better performance is obtained when the proposed PDFLC is applied.

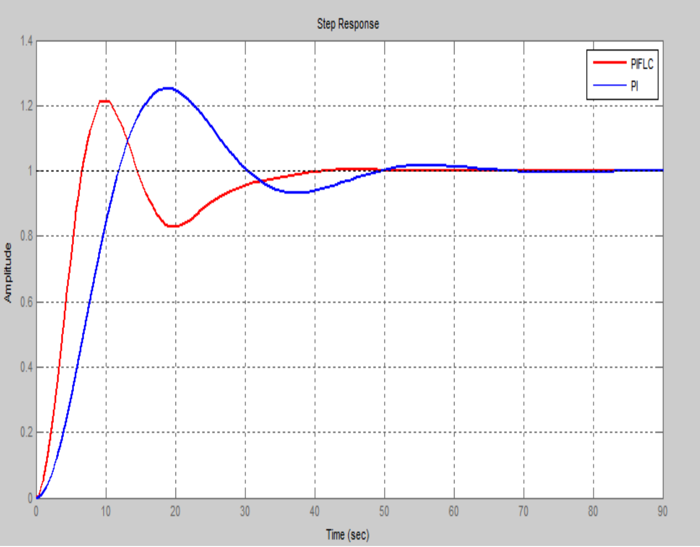


Fig. 17 Comparative between the response of PI and PIFLC.

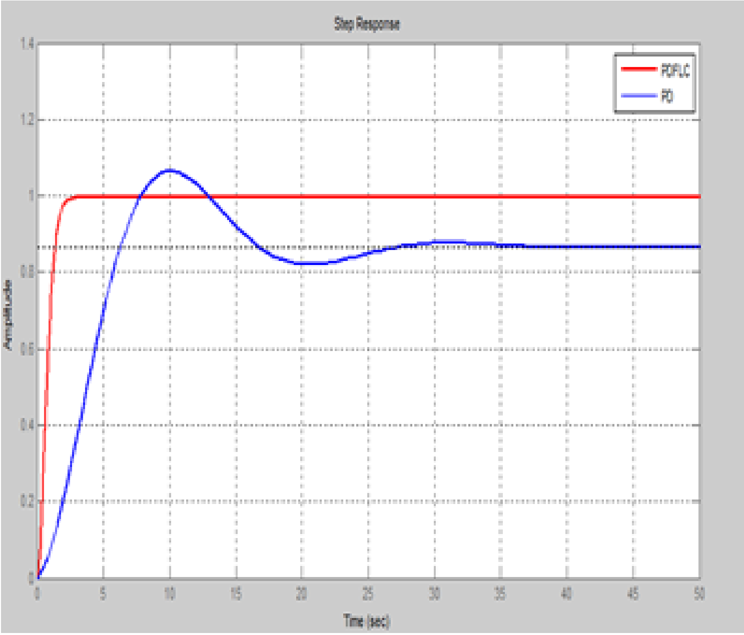


Fig. 18 Comparative between the response of PD and PDFLC.

To summarize the work done in this paper and give a final estimation of the results obtained, a comparison among the proposed controllers is shown in fig 19. It is clear these figures that implementing the PDFLC controller not only decreases the rise time, but also it eliminates the overshot of the response. Table 6 compares the performance of the investigated controllers. From the results provided in this table, it is obvious that the proposed PDFLC has a far better performance.

Table 7. Different performance indices to evaluate the proposed controllers.

Controller	Rise Time	Overshoot	Settling Time	S.S Error
PI	8.06 Sec	25.3 %	46 Sec	0 %
PIFLC	4.34 Sec	1.215 %	38 Sec	0%
PD	4.49 Sec	23 %	24.9 Sec	13.4 %
PDFLC	1.2 Sec	0 %	2.6 Sec	0 %

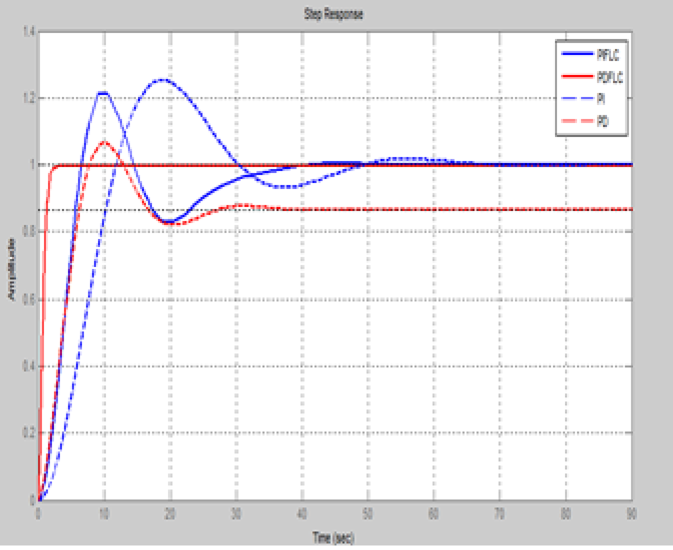


Fig. 19 Comparative among the response of PI, PIFLC, PD, and PDFLC.

V.CONCLUSION

This paper deals with the design of a PDFLC to control the concentration of the linear model of Continuous stirred tank reactor CSTR. This system is a typical chemical reactor with high nonlinearity characteristics. In order to design an efficient controller for the product of concentration in CSTR, an accurate mathematical model of the system was firstly derived. Then several controllers were applied. Trial and error technique was used to tune the parameters of the investigated controllers. From the simulation results, it is noticed that the proposed PDFLC gives better dynamic performance in terms of less undershoot, less overshoot, less settling time, and less rise time. Accordingly, the superiority of the proposed PDFLC approach is demonstrated. This is achieved by comparing the results from the proposed approach with other investigated controllers such as PD, PI, and PIFLC.

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