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Modeling and intelligent control of two tank Continuous Stirred Tank Reactor Systems (CSTRs) using Fuzzy logic Controller

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ABSTRACT

A two tank Continuous Stirred Tank Reactor (CSTR) is a typical chemical reactor system with highly non-linear characteristics where an efficient control of the product concentration in CSTR is achieved only through an accurate model. The dynamic model of the process is developed for a complex reaction system. A Fuzzy logic controller strategy is developed for a two tank continuous reactor system, which has high nonlinearity and wide operating range for a complex reaction system and it is compared with IMC based PID controller to control product concentration of the CSTR. Simulation studies have been carried out in MATLAB SIMULINK. The best controller has been chosen by comparing the criteria of response such as settling time, rise time, percentage of overshoot and steady state error. From the simulation studies, the Fuzzy controller has better performance than the conventional PID controller.

Keywords— *Continuous Stirred Tank Reactor, Fuzzy logic controller, IMC PID controller, Dynamic modeling, MATLAB SIMULINK*

1. INTRODUCTION

In any manufacturing process, the chemical reactor is the heart of the process plant. Continuous Stirred Tank Reactors (CSTRs) are commonly used chemical equipment and also important technological sectors of the chemical process industry, which exhibits highly nonlinear behavior and usually have wide operating ranges. In CSTRs multiple reactions occur in a liquid medium. Most of the chemical reaction systems are complex in nature and difficult to analysis and control.

In addition, nowadays CSTRs often have to operate in multiple operating regions to manufacture several different products to realize flexible manufacture and enhance competition ability. Hence, a very important control objective is to minimize the product transition time and thereby reduce the amount of off-specification product during the transition. However, its nonlinear behavior of CSTRs becomes more significant during this product transition as compared to local operation around a steady state. As a result, CSTRs provides a unique opportunity for employing a novel control technique.

Controlling of process plants requires the knowledge of process control. An automatic controller must able to facilitate the plant operation over a wide range of operating conditions, The PI and PID controllers are commonly used in many industrial control applications. These controllers are tuned with different tuning techniques to address satisfactory plant performance. However, specific control problems associated with the plant operations s severely limit the performance of conventional controllers. The increasing complexity of plant operations together with tougher environmental regulations, rigorous safety codes and rapidly changing economic situation demand need for more advanced and sophisticated controllers.

Generally, controllers are used to rejecting disturbances and to implement set point changes. In theory, a controller can be used to control any process which has a measurable output, a known ideal value for that output and an input to the process that will affect the relevant PV. The design of a PID controller for the system is presented. There are many techniques to design and tune a PI and PID controllers (America Morales et al., 2000, Skogestad et al., 1986). Recently, M.Saad, A. Albagul and D.Obiad (2011) have developed a mathematical model and studied the simple concentration variation process using the transfer function modeling and controller is tuned by using the Ziegler Nicholas method. Ang Li, M.S. (2008) investigated the Model predictive control (MPC) strategy and compared the control effects with a Proportional-Integral-Derivative (PID) control strategy in maintaining a water level system. J. Prakash and K.Srinivasan (2009) have studied on Model Predictive Controller with CSTR and different set of controller settings for each operating system. Tuning the PID controller with IMC controller by K_p, K_i, K_d even changing one of these variables can change the effect of the other two. R. Suja Mani and T. Thyagarajan (2009) have studied to model the CSTR incorporating its non-linear characteristics. Two nonlinear models based control strategies namely internal model control and direct inverse control were designed using the neural networks and applied to the control of isothermal CSTR. Jose Alvarez-Ramirez, America Morales (2000) have explored the PI contribution of novel stability analysis of a wide class of CSTR. Using in a Classical PI controller of single Reactor using process control. A complex PID problem of CSTR is solved making it so easy. Most of the literature reported are on single tank reactor system but limited work has been carried out on two tanks CSTRS that is mostly on the design of PID controller. Hence, the design of a controller for two tank system with intelligent controlling provides an opportunity.

A two tank continuous stirred tank reactor as shown in figure 1 is a typical reactor system with complex nonlinear characteristics. The concentration of the outlet flow of the two chemical reactors will be forced to have a specified response. It is assumed that the overflow tanks are well mixed isothermal reactors, and the density is the same in both tanks. Due to assumptions for the over flow tanks, the volumes in the two tanks can be taken to be constant and equal. It is desired to control the second tank based on the concentration in the first tank. Although the conventional PID controllers have been applied in the feedback loop mechanism and extensively used in industrial process control. Limitations of traditional approaches with constraints are the main reasons for emerging powerful and flexible controllers. In the present study and IMC based PID and Fuzzy logic controller for unstable continuous stirred tank reactor are proposed to control the concentration of non-linear CSTR. The performance of the Fuzzy controller is compared with the conventional IMC based PID controller using MATLAB SIMULINK. Finally, the objective of this work is to design and select the best controller for the system that can control the concentration of CSTR.

2. DYNAMIC MODELING SIMULATION

In CSTR System the concentration of the outlet flow of two chemical reactors will be forced to have a specified response in this section. Figure 1 shows a simple concentration process control. Reaction involved is $A \rightarrow B$.

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. 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.

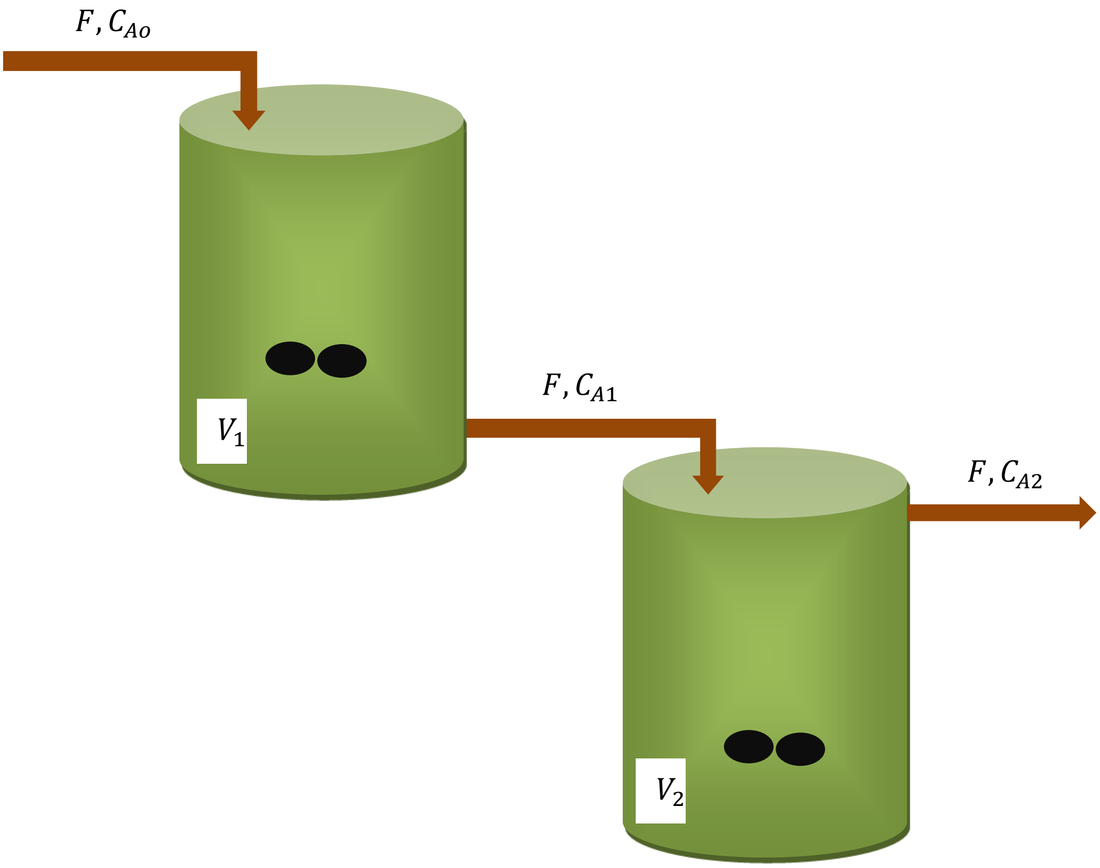

Fig. 1: Schematic diagram of Two CSTR systems in series

The component balance of A of the first tank can be obtained as

$$V_1 \frac{dC_A}{dt} = FC_{Ao} - FC_{A1} - VkC_{A1} \tag{1}$$

V_1 = Volume of the First Tank, F = Flow rate, C_{Ao}= Inlet Concentrate of the first tank, C_{A1} = Outlet Concentrate of first tank and inlet of the second tank

Equation 1 rearranged as from Equation (2)

$$\frac{dC_{A1}}{dt}+\frac{C_{A1}}{\tau_1}=\frac{FC_{Ao}}{V1} \tag{2}$$

$$\tau_1=\frac{V1}{F+KV_1} \tag{3}$$

and

$$K_{p1}=\frac{F}{F+KV_1} \tag{4}$$

We obtain the Transfer function of the first CSTR is by applying the Laplace of the equation (2)

$$\frac{C_{A1}}{C_{A0}}=\frac{k_{p1}}{(\tau_1 s+1)} \tag{5}$$

From the second CSTR rate of formation reaction, the component balance equation is

(6)

$$V_2\frac{dC_{A2}}{dt}=FC_{A1}-FC_{A2}-V_2kC_{A2} \tag{7}$$

$$\frac{dC_{A2}}{dt}+\frac{C_{A2}}{\tau_2}=\frac{FC_{A2}}{V2} \tag{8}$$

$$\tau_2=\frac{V2}{F+KV_2} \tag{9}$$

and,

$$K_{p2}=\frac{F}{F+KV_2} \tag{10}$$

Here, we get the transfer function as

$$\frac{C_{A2}}{C_{A1}}=\frac{k_{p2}}{(\tau_2 s+1)}$$

Assuming the Parameters

The flow rate is constant for the whole system $F=0.033\frac{m^3}{min}$

The volume of the two tanks is the same $V=V1=V_2=1.05\,m^3$

Reaction Rate $K=0.04\,min^{-1}$

Then,

$$\tau_1=\tau_2=\tau=8.25\text{min}$$

$$K_{p1}=K_{p2}=K_p=1.69$$

Now Transfer function of two CSTR systems by multiplying equation (5 and.9)

$$G(s)=\frac{C_{A2}}{C_{A0}}=\frac{K_p^2}{(\tau_2 s+1)^2}$$

$$\mathbf{G(s)}=\frac{\mathbf{0.669^2}}{\mathbf{S^2+0.2424S+0.0147}}$$

This is the Transfer function of the Problem

Steady State Solution:

The Steady State solutions from equation (11 and 12) are [19]

$$FC_{Ao}-FC_{A1}-VkC_{A1}=0 \tag{11}$$

$$FC_{A1}-FC_{A2}-V_2kC_{A2}=0 \tag{12}$$

Steady state Conditions are:

C_{A0} = 1 mol/m3

Flow rate = $0.033\frac{m^3}{min}$

Volume of the reactor V1 = V2 = $1.05m^3$

Reaction rate K = $0.04min^{-1}$

From equation (3.11)

$$\frac{F(C_{Ao}-C_{A1})}{V}=\frac{V}{V}kC_{A1} \tag{13}$$

$$\frac{F(C_{A0})}{V}=\frac{F(C_{A1})}{V}+\frac{V}{V}kC_{A1} \tag{14}$$

$$\frac{F(C_{A0})}{V}=(C_{A1})\left[\frac{F}{V}+\frac{V}{V}k\right] \tag{15}$$

$$\frac{\frac{F}{V}}{\left[\frac{F}{V}+\frac{V}{V}k\right]}=\frac{C_{A1}}{C_{A0}} \tag{16}$$

After substituting steady-state conditions, the resulted equations are

$$\frac{C_{A1}}{C_{A0}}=0.5 \tag{17}$$

$$C_{A1}=0.5 \tag{18}$$

Substitute equation (17) value in equation (11) we will get

$$FC_{A1}=C_{A2}(F-V_2k) \tag{19}$$

$$\frac{F}{(F-V_2k)}=\frac{C_{A2}}{C_{A1}} \tag{20}$$

$$\frac{C_{A2}}{C_{A1}}=0.4 \tag{21}$$

$$C_{A2}=0.2 \tag{22}$$

Steady State Variables are:

$$C_{A0}=1\ \mathrm{mol/m^3}$$

$$C_{A1}=0.5\mathrm{mol/m^3}$$

$$C_{A2}=0.2\mathrm{mol/m^3}$$

3. DESIGN OF THE CONTROL STRATEGY FOR THE TWO TANK SYSTEM

A two tank Continuous Stirred Tank Reactor (CSTR) is a highly non-linear process, particularly when the chemical reaction is involved. The heat energy will be either liberate or absorbed by the reactor due to the reaction. The control of temperature and product concentration for this process is a real challenge due to non-linear temperature changes during the reaction. Hence, the conventional controller can be replaced with intelligent controllers like fuzzy logic controller which generate a fast dynamic response. Compared to conventional controller's fuzzy logic controllers are better in complex problem-solving.

In this section, a control strategy for the two tanks CSTRs is presented based on first principles model. The various controllers have been designed and performances are compared for the CSTR process. The control strategy for two tanks CSTR is developed by are the IMC based PID and Fuzzy logic controller. The first step is to test the performance of the system for a step change in the input without a controller to examine the uncontrolled response. The response of the closed loop of the two tank CSTR system has been taken to see the behavior of this CSTR system in closed loop mode, where the response of this system with different control strategy is carried out using SIMULINK. The design of a controller for the two tanks CSTR is presented and investigated using IMC based PID and Fuzzy logic control strategy. To design the PID controller for two CSTR systems, MATLAB Simulink platform is used. The schematic of the PID controller in the Simulink platform is shown in figure 2.

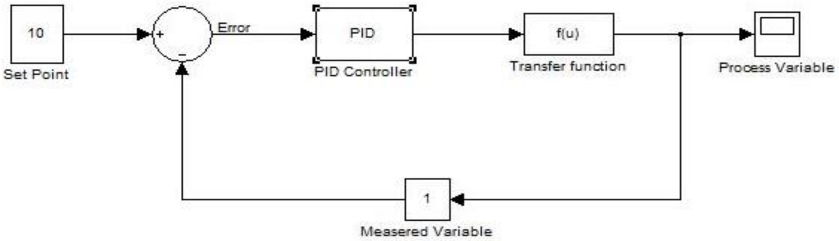

Fig. 2: Schematic diagram PID

The time domain equation of the PID controller,

$$u(t)=k_pe(t)+K_I\int_0^t e(t)dt+K_d\frac{de(t)}{dt}$$

PID controllers have been the most widely used controller in the industry for the past decades because of its simplicity and efficiency. But, tuning of the gains of the PID controller appropriately is always an attractive problem. One of the most popular tuning methods is the Ziegler-Nichols method but it is a time-consuming technique. The PID controller tuning is a method of computing the three control parameters Proportional gain, Derivative time and Integral time, such that the controller meets desired performance specification. Since the exact dynamics of the plant is generally unknown. The IMC uses a model based procedure, where a process model is embedded in the controller. For a two tank CSTR, a model of process decides reactant concentration that needs to be added to the process to obtain the desired concentration profile, specified by the set point.

3.1 IMC based PID controller design

The IMC structure is shown in figure 3. The process model receives the same manipulated variable as the actual process and subtracts the difference between the process output and process model output to determine the model error. In IMC structure disturbance effects the calculation of model uncertainty which includes unmeasured disturbances. This information can be used by the controller to compensate for the model uncertainty. IMC provides transparency for control system designing and tuning.

The IMC based PID structure uses the process model. In the IMC procedure, the controller is directly based on the invertible part of the process transfer function. The IMC results in only one tuning parameter which is filter tuning factor but the IMC based PID tuning parameters are the functions of this tuning factor. The selection of the filter parameter is directly related to the robustness. IMC based PID procedures uses an approximation for the dead time. And if the process has no time delays it gives the same performance as does the IMC. In ideal IMC structure, the point of summation of the process and the model output is moved as shown in figure 3 to form a standard feedback controller which is known as IMC based PID controller.

The closed-loop simulations are performed for the above procedure and by adjusting the tuning parameter, considering a trade-off between performance and robustness that is sensitivity to model error.

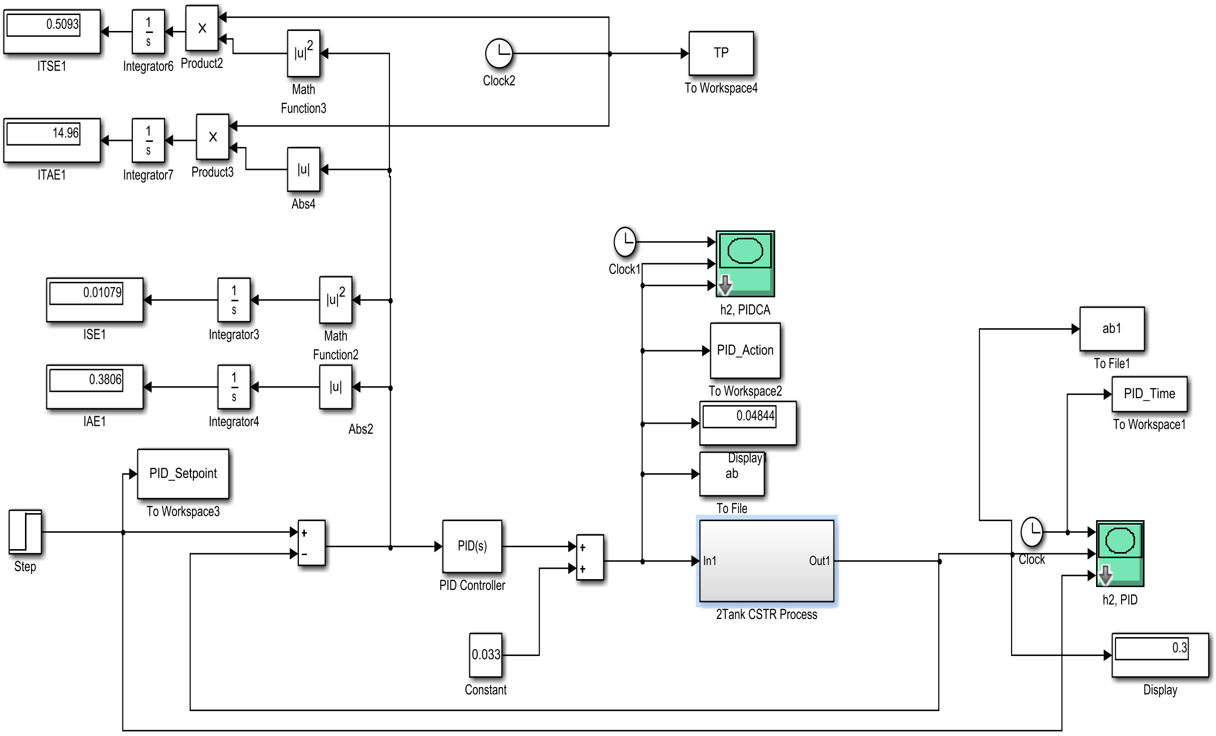

Fig. 3: Block diagram of Two Tank CSTR process using IMC-PID Controller

3.2. Fuzzy Logic controller design

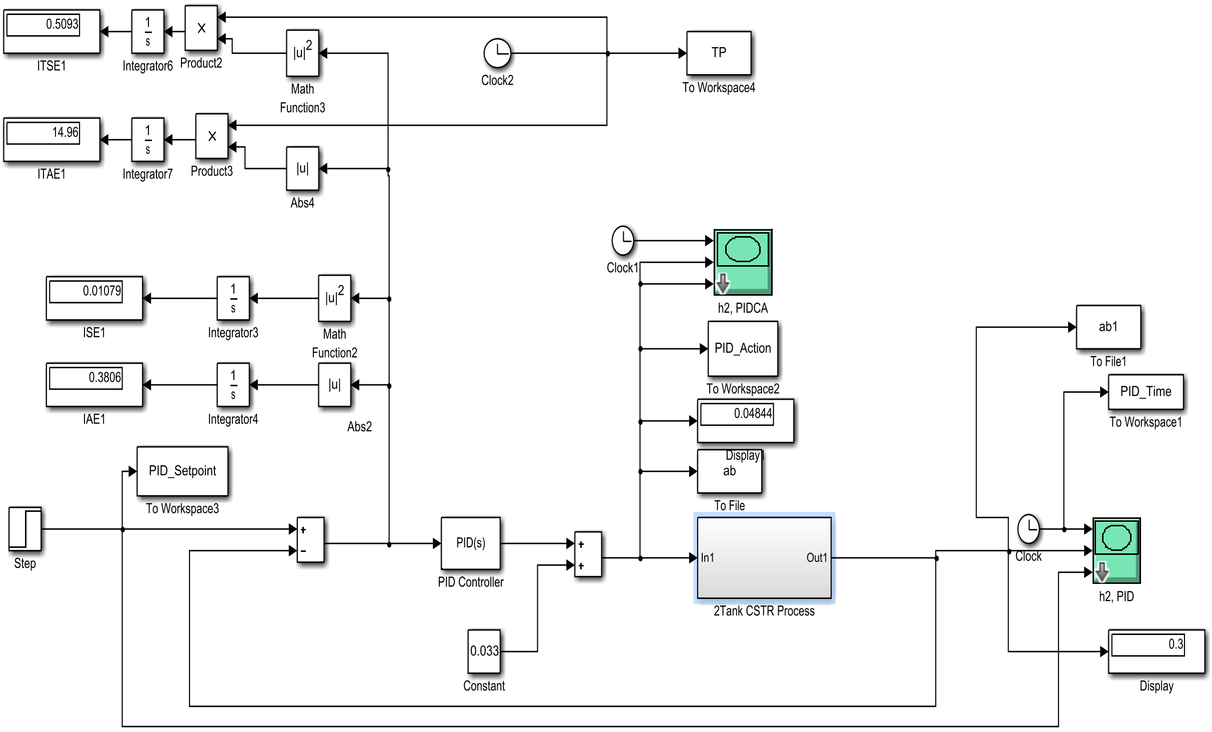

Fig. 4: Block diagram of Two Tank CSTR process using Fuzzy logic Controller

The principle of the fuzzy logic is to approximate the system behavior, where numerical functions or analytical functions do not exist. Hence, Fuzzy systems have a high potential to understand the systems that are devoid of analytical formulations in a complex

System. Complex systems can be a new system that has not been tested, they can involve human conditions such as biological or medical systems. The ultimate goal of the fuzzy logic is to form the theoretical foundation for reasoning about imprecise reasoning; such reasoning is known as approximate reasoning. Fuzzy logic controller, require a multiplexer to give input to the controller. The inputs to the controller are an error (difference of the set point and output) and feedback output (output as the feedback). The fuzzy controller presented in figure 4 is applied for the continuous stirred tank reactor system. The constructed membership function has been used for the inputs and the output taking triangular memberships. Using these values, fuzzy rules in the fuzzy rule base editor and the response is observed that there is no inverted response, no overshoot, no undershoot, rise time and settling time is reduced. A simulation study was carried out to establish the effectiveness of the proposed methods in controlling the reactant concentration and to predict the dynamic process behavior with tuning the parameters of the controllers.

4. RESULTS AND DISCUSSION

The simulation results of IMC Based PID Controller and FLC are shown in figures 5 to 16 respectively. The simulation results show that the FLC controller has no overshoot and fast response compared to the conventional IMC based PID controller. The FLC controller designed in this work shows good response in the entire operating region of the CSTR which has highly non-linear characteristics. The controller operates in a regulated manner so that any disturbance to the system is eliminated. The controller was designed to control the product concentration of CSTR by varying the flow rate of one of the inlet stream. The FLC designed for CSTR as shown in figure 4 showed the best performance for both set point tracking and regulatory conditions. The response of the concentration of the second reactor with respect to the time is observed when the setting point in the concentration of A from 0.2 to 0.3 mol/m^3. Figure 5 and 6 shows response and manipulated variable of the CSTRs, these figures indicate that FLC performance is better in terms of overshoot and response time. The corresponding performance index for both the controllers are measured in terms of IAE, ISE, ITAE and ITSE and presented in table 1, the table 1 indicates that FLC showing lower when compared to IMC based controller.

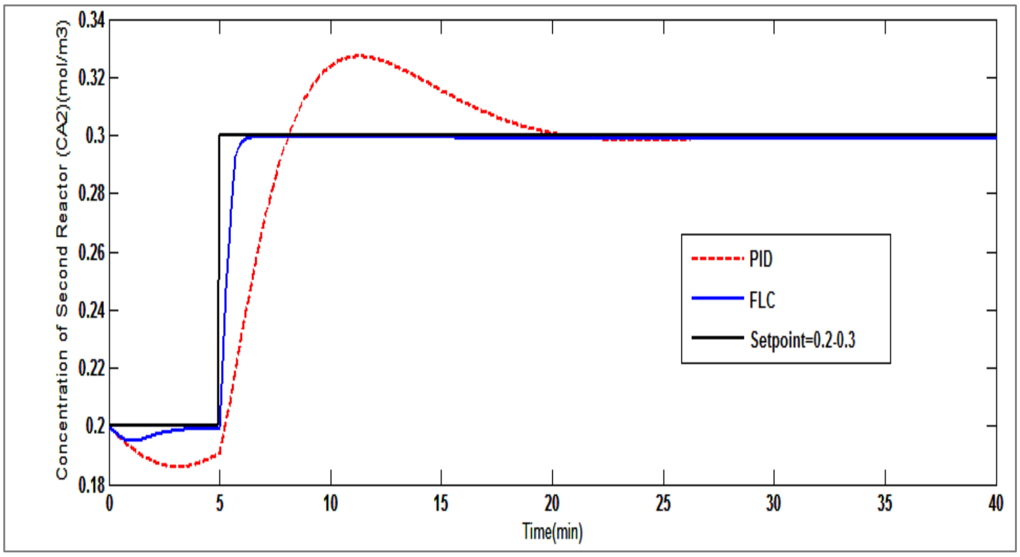

Fig. 5: Comparison of Closed Loop Response in Concentration of the second reactor between FLC and PID controller from set point change in concentration of A from 0.2 to 0.3 mol/m^3

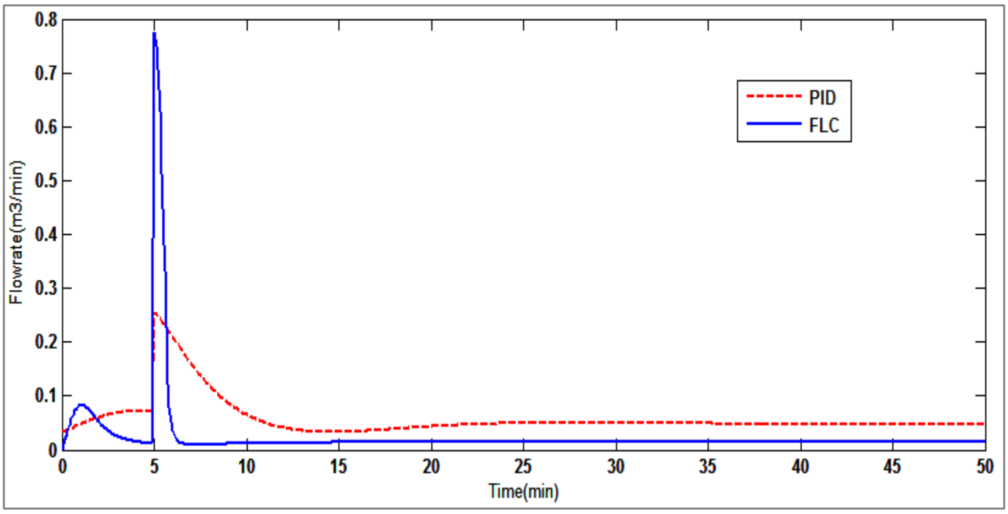

Fig. 6: Comparison of Manipulated Variable (Flow rate) in feed for the response in the concentration of A from 0.2 to 0.3 mol/m^3

Tables 1: Performance of controllers when the concentration of reactant A from changed from 0.2 to 0.3 mol/m^3

Set Point=0.2-0.3	IAE	ISE	ITAE	ITSE
PID	0.3961	0.0151	3.658	0.1078
FLC	0.08643	0.002285	1.341	0.01252

To test the robustness of the designed controllers, controllers are subjected to different conditions like changing the input to the controller from 0.2 to 0.4 mol/m^3, variations in the input from set point to ±10% and variations in the reaction conditions that is rate constants (K1andK2) changed within ±10 % are subjected and the performance of controllers and corresponding manipulated variable reported from figure 7-16. The corresponding performance index values of both IMC based controller and FLC based controllers are reported from the tables 2-6. The results show that the proposed fuzzy logic controllers show better control of the concentration of the reactant than the other controllers like IMC based PID.

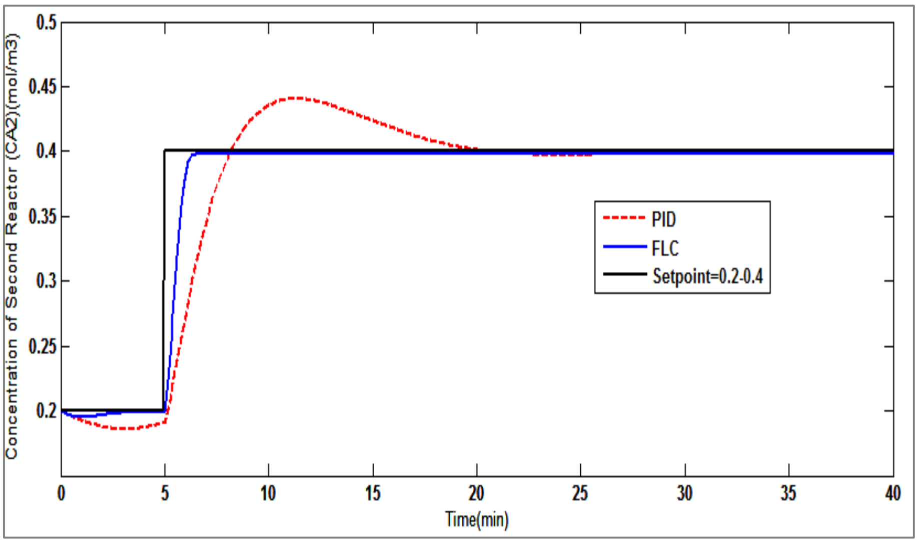

Fig. 7: Comparison of Closed Loop Response in Concentration of the second reactor between FLC and PID controller from set point change in concentration of A from 0.2 to 0.4 mol/m^3

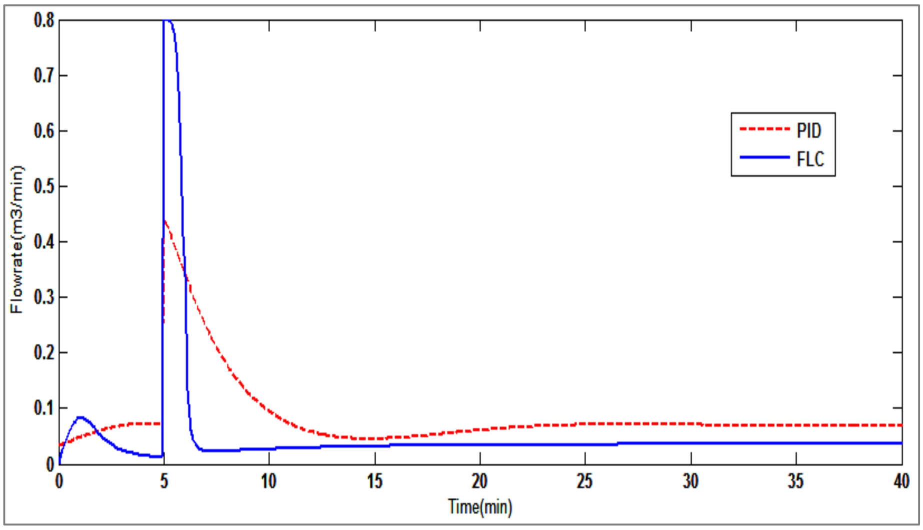

Fig. 8: Comparison of Manipulated Variable (Flow rate) in feed for the response in setpoint change in concentration of A from 0.2 to 0.4 mol/m^3.

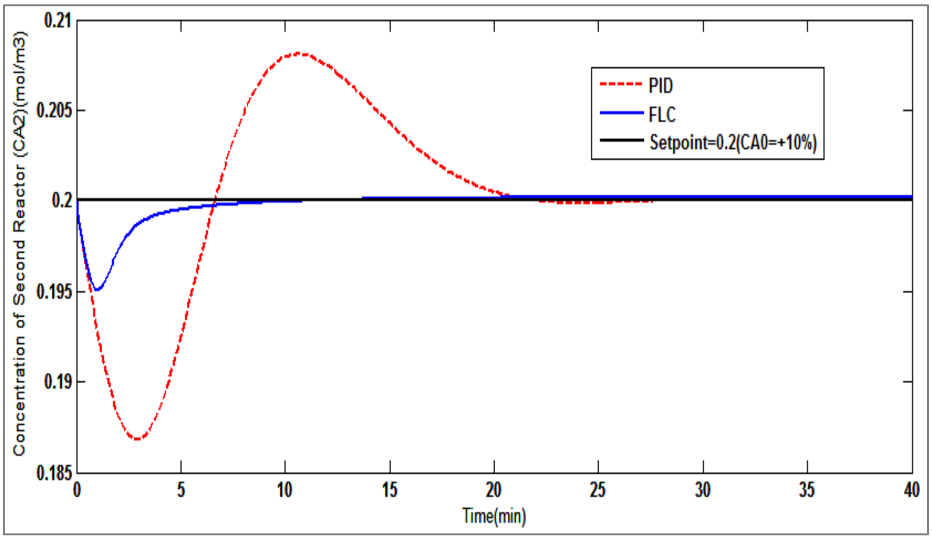

Fig. 9: Comparison of Closed Loop Response of Concentration in the second reactor between FLC and PID controller with disturbance in the initial concentration of +10% (C_{Ao}= 1.1mol/m^3)

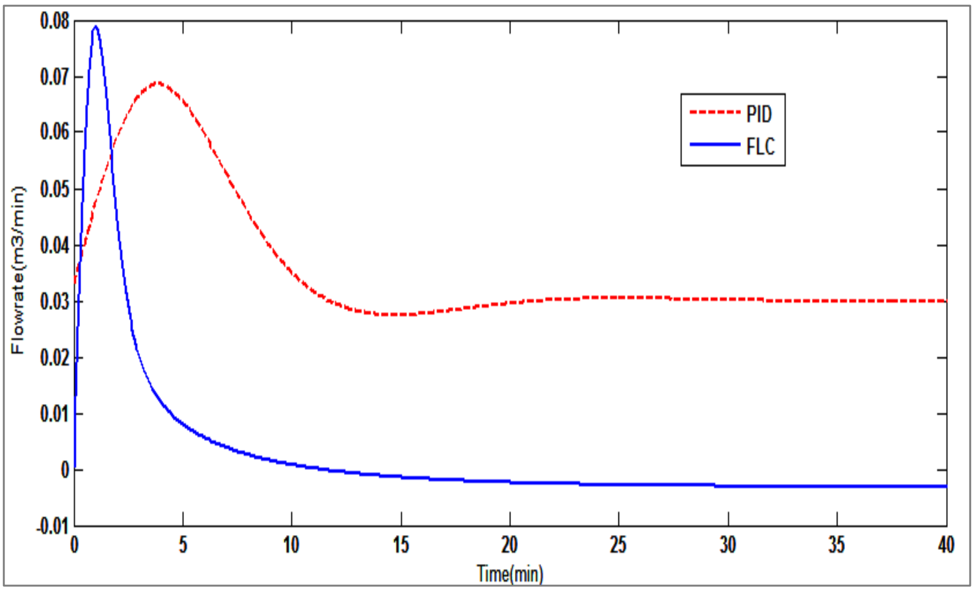

Fig. 10: Comparison of Manipulated Variable (Flow rate) in feed for the response with disturbance in the initial concentration of +10% (C_{Ao}= 1.1mol/m^3)

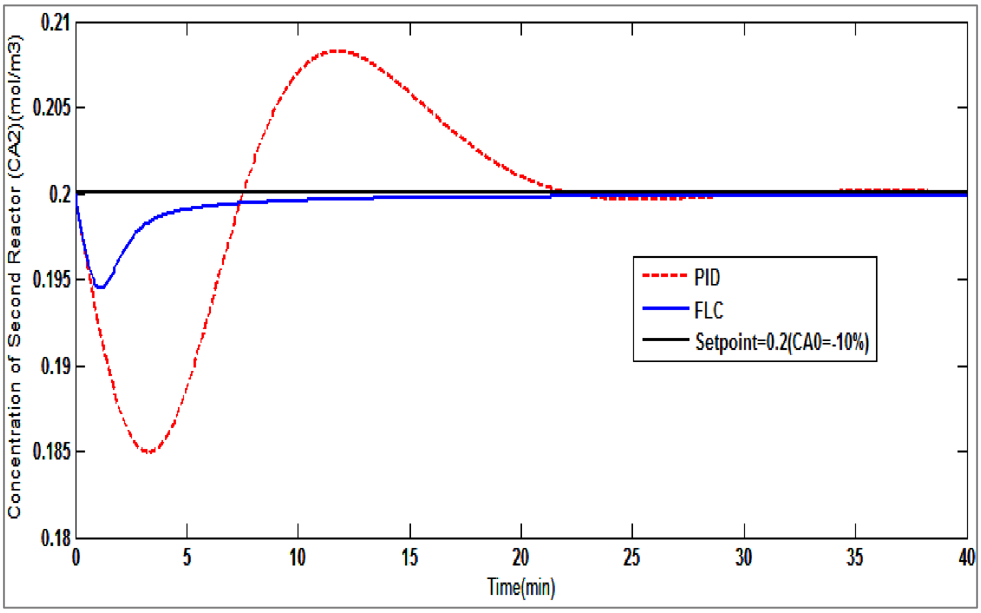

Fig. 11: Comparison of Closed Loop Response of Concentration in the second reactor between FLC and PID controller with disturbance in the initial concentration of -10% (C_{Ao}= 0.9mol/m^3)

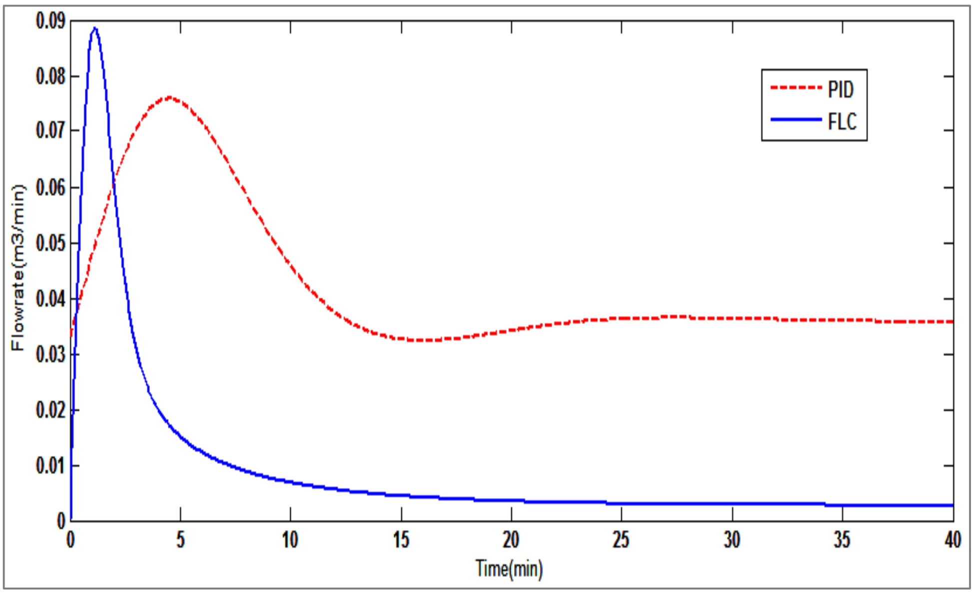

Fig. 12: Comparison of Manipulated Variable (Flow rate) in feed for the response with disturbance in the initial concentration of -10% (C_{Ao}= 0.9mol/m^3)

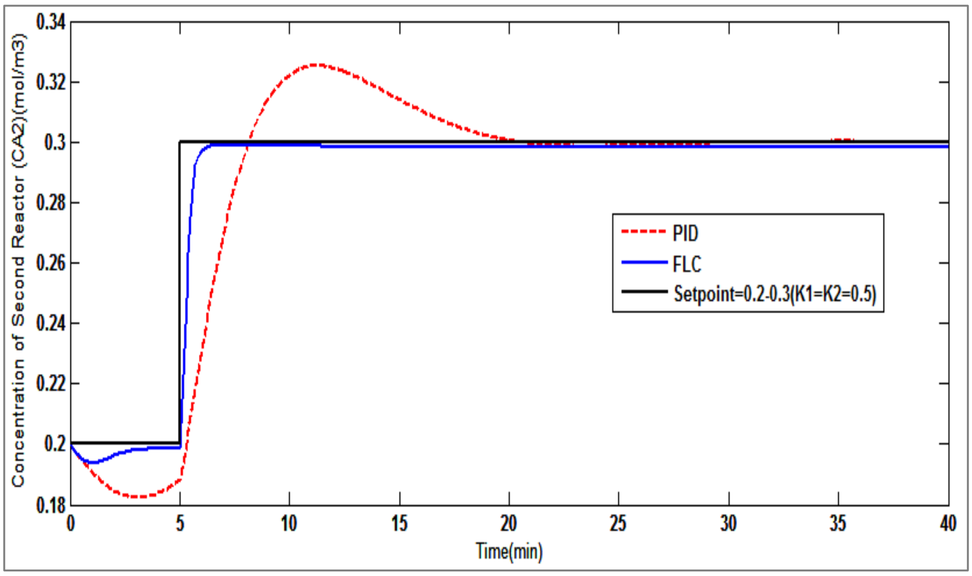

Fig. 13: Closed Loop response in Concentration of Second reactor with FLC and PID controllers with change in rate constant +10% (K1=K2 = 0.05min^{-1})

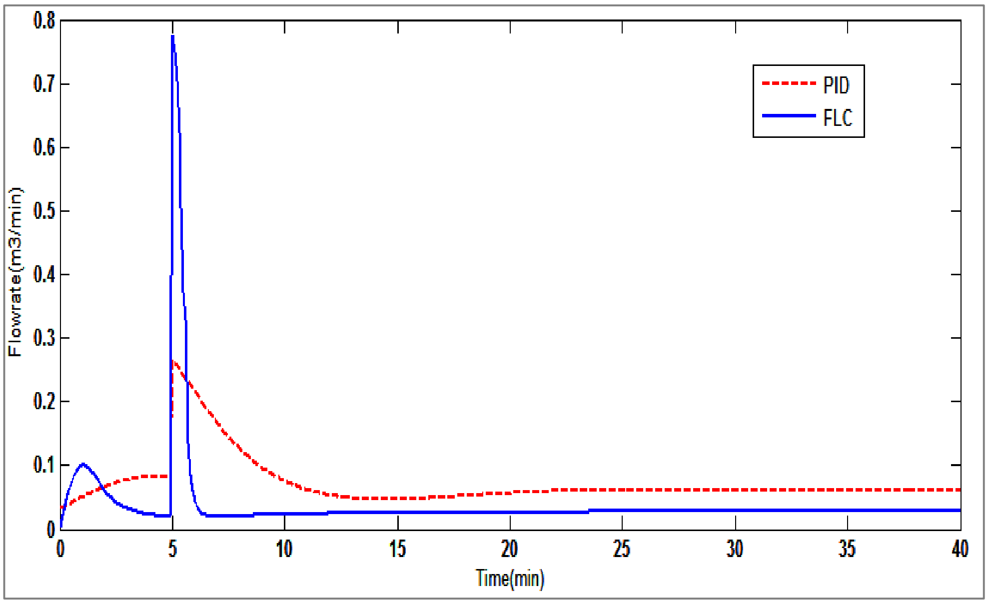

Fig. 14: Comparison of Manipulated Variable (Flow rate) in feed for the response with change in rate constant +10% (K1=K2 = 0.05min^{-1})

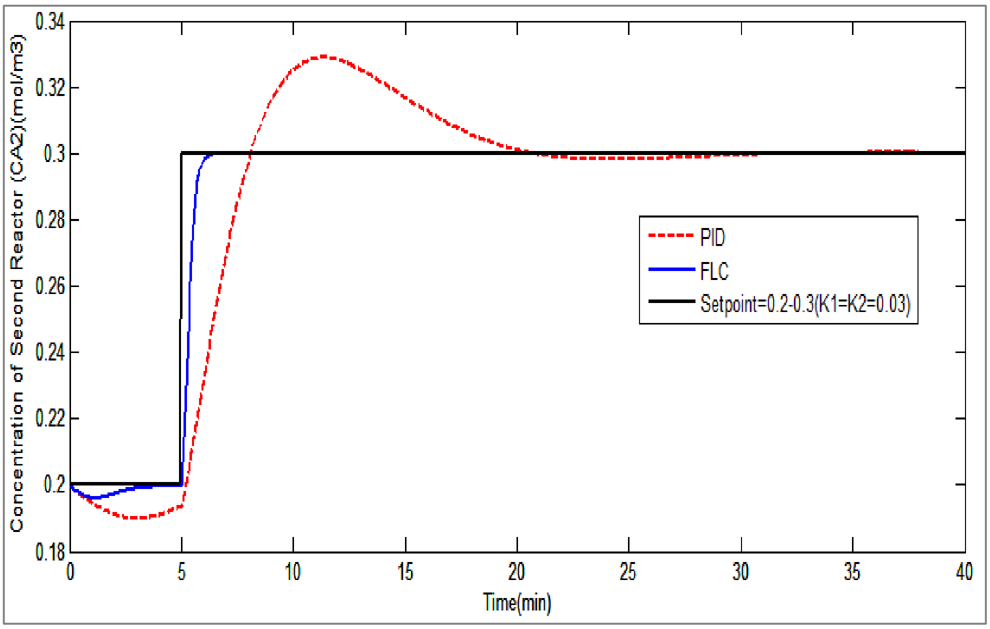

Fig. 15: Closed Loop response in Concentration of Second reactor with FLC and PID controllers with change in rate constant -10% (K1=K2 = 0.03min^{-1})

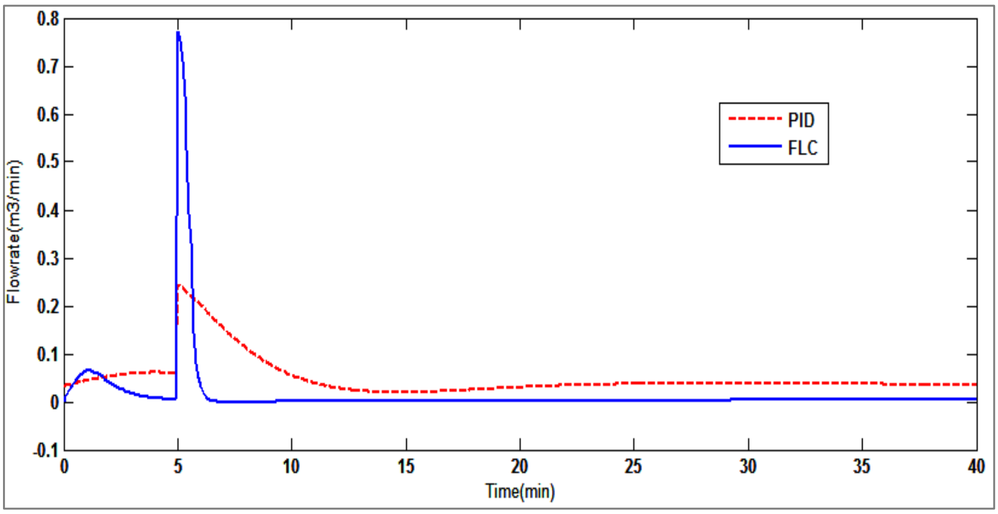

Fig. 16: Comparison of Manipulated Variable (Flow rate) in feed for the response of controllers with a change in the rate constant -10% (K1=K2 = 0.03min^{-1})

Tables 2: Performance of controllers when the concentration of reactant A from changed from 0.2 to 0.4 mol/m^3

Set Point=0.2-0.4	IAE	ISE	ITAE	ITSE
PID	0.6256	0.04706	5.794	0.3189
FLC	0.2096	0.01445	3.225	0.08069

Table 3: Performance of controllers when the concentration of reactant A from changed +10% deviations from set point 0.2 mol/m^3

Set Point=0.2(CA0=+10%)	IAE	ISE	ITAE	ITSE
PID	0.1174	0.0009249	0.9655	0.005905
FLC	0.01819	0.00000352	0.2408	0.0000087

Table 4: Performance of controllers when the concentration of reactant A from changed -10% deviations from the set point 0.2 mol/m^3

Set Point=0.2(CA0=+10%)	IAE	ISE	ITAE	ITSE
PID	0.1376	0.00122	1.177	0.007863
FLC	0.02297	0.00000525	01944	0.0001199

Table 5: Performance of controllers when the rate constant changed +10% deviation from the set point 0.2 to 0.3 mol/m^3

Set Point=0.2 to 0.3 (K1=K2=0.05(+10%)	IAE	ISE	ITAE	ITSE
PID	0.3942	0.01522	3.443	0.1037
FLC	0.1047	0.00233	1.499	0.01349

Table 6: Performance of controllers when the rate constant changed -10% deviations from the set point 0.2 to 0.3 mol/m^3

Set Point=0.2 to 0.3 (K1=K2=0.05(+10%)	IAE	ISE	ITAE	ITSE
PID	0.3956	0.01506	3.834	0.1123
FLC	0.04964	0.00228	0.338	0.01177

5. CONCLUSION

In the present research work, the performance of two tanks CSTR for reversible chemical reactions using IMC based Proportional Integral derivative(PID) control and Fuzzy logic control by subjecting servo and regulatory problem. It is found that fuzzy logic controller performing well in terms of settling time and rise time and another parameter like ISE, IAE, IATE, Etc. There is a peak overshoot in the response with IMC based PID controller, where as Fuzzy logic controller has no over shoot with least rise time, delay time and settling time. Based on simulation studies using the Simulink, it is found that for the non linear systems such as CSTR processes fuzzy controller performance is better than PID controller

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