Design And Development Of Ph Neutralization Process :
A Fuzzy Logic Based Electronics Sensing And Control System

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ABSTRACT

pH process is a chemical process of acid and base reaction in a aqueous solution. In many chemical process industries, pH measurement and controlling is extensively used to yield a good quality product. The pH control is a difficult puzzle to solve due to strong nonlinear characteristics and utmost sensitivity to various disturbances in the process.

In this paper a specific fuzzy controller (FL) is developed for control or regulation of pH parameter of pH process, which is carried out in a Continuous Stirred Tank Reactor (CSTR). Benchmark PID (Proportional + Integral + Derivative) controller is primarily used for comparative study. The model of fuzzy pH control process considered has highly nonlinear characteristics with time delay. Overall process properties are described in terms of nolinearity and robustness. Design and development of fuzzy control (FLC) carried out based on the fuzzy set theory and classical control principle. In FLC design the classical control principles have been implemented on the apparatus of approximate reasoning of Fuzzy Logic. In this practical study Fuzzy Model (FM) describes the human intelligent knowledge and excellent pH control experience of expert operator without mathematical format.

Current work present the how FLC is a powerful alternative to the conventional methods and **is suitable and convenient as it directly deals with non-stationary and uncertain behavior of pH process.**

Experimental results obtained demonstrate that fuzzy based controller is effective and potentially benefit for this typical and difficult control problem.

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1. INTRODUCTION

Acid base reaction is one of the important chemical processes. In this connection pH is the fifth important parameter. pH value depends upon the many factors like nature of acid and base, stirring speed, temperature etc., which is, require to maintaining at desired value or controlled to yield good quality product. In many chemical process industries like refining industries, waste water plant, digestion process, biochemical processes and mechanical engine's coolant system, pH measurement and controlling is very difficult due to its great sensitivity to disturbance and parameters uncertainties.

The utmost non-linearity of pH process makes the control by a conventional linear PID controller difficult. Auto tuning, adaptive control and Internal Model Based Control (IMC) [1] have been suggested and recently many nonlinear control strategies like Ratio Control, Cascade Control Feed-forward Control, Global Linearisation etc. have been employed to control pH [2]. Many workers have been made control efforts on this typical and tough control problem. However, all these techniques require mathematical algorithm and require expressing the process in terms of its mathematical analysis. For recent years, fuzzy Control has being widely investigated in theories and in applications. Generally, fuzzy control and is based on fuzzy set theory and logic which can be used to express human knowledge in mathematical format. Where, traditional control strategies are fails to do. This paper attracted to build up Fuzzy Logic Controller (FLC) based on human experts knowledge of pH process. Fuzzy controller is the best alternative to conventional PID controller to handle such a nonlinear process. Paper describes design and development of Fuzzy Controller.

To realize this, laboratory scale prototype Continuous Stirred Tank Reactor (CSTR) has been fabricated, Three-mode controller (PID) is developed, and is used to control the CSTR in which ***acid-base reaction*** takes place and makes it more stable with respect to any environmental disturbances. The PID control loop depends on three constants of *proportional, integral,* and *derivative.* Incorporating various auto-tuning rules makes the controlling stability of CSTR more sophisticated [3]. A computer is used as a supervisor of the system and required software has been developed using MATLAB. The test runs have been carried out, data is colleted and process characteristics, controllability, performance are studied for further development of the system.

Finley paper presents the comparative study between conventional PID controller and Fuzzy Logic Controller performances.

2.CONTINUOUS STIRRED TANK REACTOR (CSTR) pH PROCESS CONTROL

The Figure (1) shows pH process of weak acid (acetic acid) and strong base (Sodium hydroxide) in a well stirred reactor tank. This kind of process widely be found in chemical industries and textile industries.

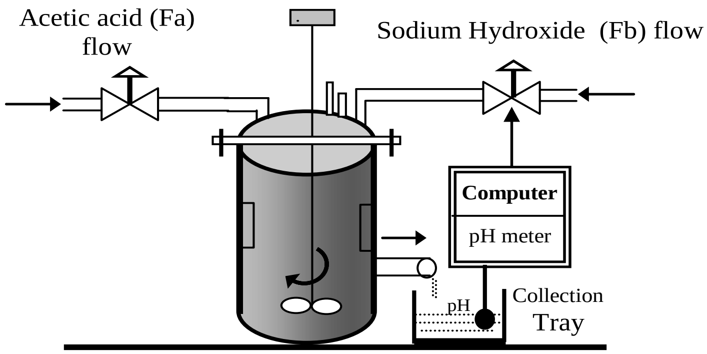

Fig. (1) : Schematic of pH Process in CSTR

The reactor has two inlets and one outlet. One input stream is of acetic acid ($HC_2H_3O_2$) and other of sodium hydroxide (NaOH). The flow rate of acetic acid is maintained constant, while the controller manipulates flow rate of the sodium hydroxide. Due to the incomplete dissociation of acetic acid in water and the equilibrium reaction with sodium acetate, the system will behave like the buffer solution of varying pH from 5.0 to 11.0 and it depends on the **flow rate**, concentrations of the incoming solutions, room temperature, stirring speed, etc.[4,5] .

The control objective is to maintain the pH value at the desired point in the constant acid flow from the acid tank by regulating the flow of base. Under ideal conditions no any polluting reagent in the tank solution. According to dynamics study nonlinearity of such system is not too serious to deal with. However in industrial practices direct measurements basically are pH values, it reflects high nonlinearity via its definition itself as below :

$$pH = -\log_{10}[H^+] \ldots\ldots\ldots\ldots\ldots \quad (1)$$

Equation (1)shows that negative of the ten-based logarithm of the H+ ion activity. According to the chemical equilibrium, the product of $[H^+]$ and $[OH^-]$ is approximately equal to :

$$[H^+][OH^-] = 10^{-14} \quad (mol/l)^2 \ \ldots\ldots\ \ldots\ldots\ldots\ldots \quad (2)$$

Which is accurate at temperature 25^0 C and fond to be high sensitive at the neutrality point (pH = 7) [6].

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In this connection, the CSTR is controlled using the ***digital PID controller***. The controller is supervised by a ***Personal Computer,*** which also helps in ***data acquisition and storage***. A Mechanical Stirrer can achieve uniform mixing of solutions in the CSTR. The pH in the CSTR can be maintained at a desired ***set point*** by manipulating the control valve on the ***base*** stream.

The auto tuning of PID controller was carried out using closed loop tuning method. Process characteristics were measured and optimum values of K_c, T_i and T_d were obtained. To obtain the quality results, PID controller was designed using Ziegler-Nichols closed loop method [7,8].

In this method, controller settings are based on the conditions that generate the loop of the process. Auto tuning results of PID controller in ***real time run setup*** has been carried out. Computer software has been developed using MATLB, to control the processes parameters loop. For various setpoint (SP= pH value) percent flow rate and corresponding pH value colleted in data (*.dat) and retrieved for simulation study using MATLAB6.5 [9]. Sample graphical results are as shown in Figure (2).

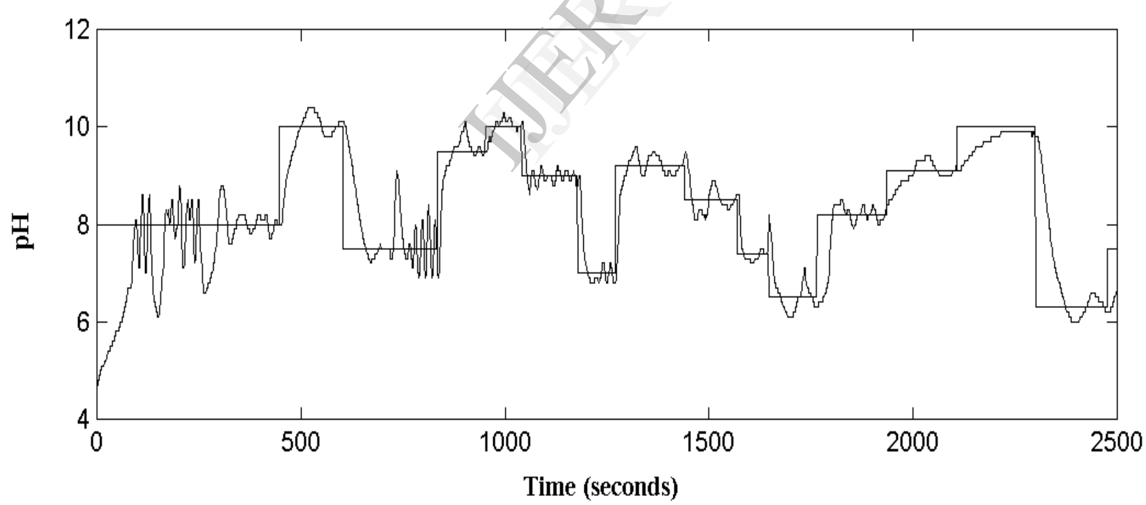

Fig. (2) : PID controller response

However, the observations signify that control system becomes ill and shows weakness in controllability. Therefore, proposed fuzzy logic stands better alternative to improve the systems performance.

Some times PID controller gives unexpected results even though tuning is proper. It shows instability for long time. Thus expected control fails from one or more reasons as stated below [10].

1) Disturbances introduce feedback delay.
2) Disturbance due to noise (mechanical, vibration, etc.)
3) Acid base reaction delay in attaining pH Value in CSTR
4) External distraction of pH value disturbs system.
5) Sudden change in process parameters.
6) System shows controllability during the transient period but fails to show later.

This paper proposes a design strategy, which makes the use of known PID design techniques, before implementing the Fuzzy Logic pH Process Controller (FLPPC). The next section describes the design and development of Fuzzy Logic pH Control (FLPC) System.

3. DESIGN AND DEVELOPMENT OF FUZZY LOGIC pH CONTROL (FLPC) SYSTEM

Fuzzy based controller is set up for a CSTR with the standard configuration shown in Figure 1.

Phases involved in development of FLPC are as follows-

- Process Identification
- Fuzzification and Knowledge Representation
- Rule base and Inference Scheme
- Defuzzification

Process Identification –

This is one of the important phases of development of FLPC system. FLPC requires an understanding of complete knowledge of the pH process behavior or characteristics. Which is made available by plotting the graph of pH against flow rate of base stream at constant acid flow. To obtain this curve, the pH values are recorded with respect to time until it reaches to 11. This can be done using program developed in MATLAB-6.5. Figure 3 shows steady state characteristic nolinearity of pH process of strong base and weak acid. Curve provides all type of knowledge and information, which is utilized to controlling the pH value. Input / output domain parameters ranges also decided using identification curve. Sufficient and accurate knowledge of these parameters is essentially to run the plant for effective control of pH.

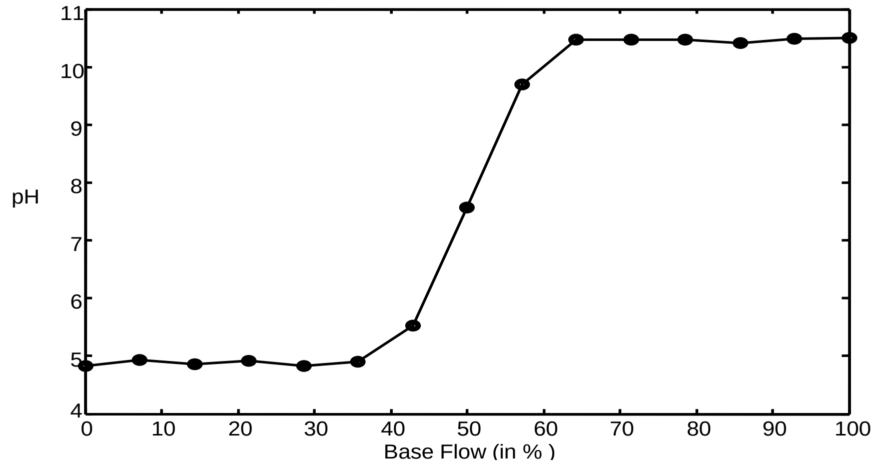

Fig. (3) Process identification Curve or reaction curve : Strong base (Sodium Hydroxide) and weak acid (Acetic acid)

Fuzzification and Knowledge Representation -

This is the second phase of design the FLPC system. Using the sufficient knowledge from process identification curve. The Fuzzification process starts with determining the input and output process variables. After complete review of conventional working of pH process, two variables viz. e and δe have been selected as fuzzy input variables and δu as a fuzzy output variable. Based on prior knowledge and empirical data of real time system, Universe of Discourse (UoD) of each variable has been worked out. The proposed **Fuzzy Logic pH Control system (FLPC)** has two inputs, error (e) of pH value and the change in error δe of pH value, which are defined as follows;

$$e(t) = y_{sp}(t)-(y(t) \text{ and } \delta e(t) = e(t) - e(t-1), \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where, y(t) is process output, $y_{sp}(t)$ desired output or set-point, and 't' is discrete time. These inputs are used in the FLPC to obtain a value of its output v(t) [11].

Operating ranges of the input/output ranges of fuzzy parameters are given in Table-1.

Table -1

Operating ranges (UoD) of Various Fuzzy Parameters

PARAMETER INPUT/OUTPUT	UOD
1. Error 'e' (input)	pH value lies between -7 to +7
2. Change in error 'δe' (input)	'δe' is different than 'e' however, it is in the range -7 to +7.
3. Change in base flow 'δu' (controller output)	Change in base flow value lies between –9 to 9.

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Section describes the various linguistic variables and membership functions for input and output domains.

The UoD of each variable is initially partitioned (fragmented) more or less uniformly into seven sub-ranges in domains known as fuzzy subset, which are further reshuffled or modified for mapping connectivity between input and output variable by fuzzy inference rules. For the easy and quick identification these sets are coded either by numbers/letters or words or both so called ***linguistic labels*** or linguistic variables For the sake of connivance and simplicity all three e, δe and δu input/output variables have been linguistically identified or labels as below.

Term set- T $\begin{bmatrix} e \\ \delta e \end{bmatrix}$ →

NL = Negative_Large,
NM = Negative_Medium,
NS = Negative_ Small,
ZE = Zero error
PS = Positive_Small,
PM = Positive_Medium,
PL = Negative_Large,

and $\begin{bmatrix} \delta u \end{bmatrix}$ →

NH =Negative High
NM=Negative Medium
NS= Negative Small
ZE = Zero output
PS = Positive small
PM= Positive Medium
PH = Positive High

Fuzzy variables have been then fuzzified using **Triangular Membership Function** (TMF), their sketches are as shown in Figure 4a, 4b and 4c respectively.

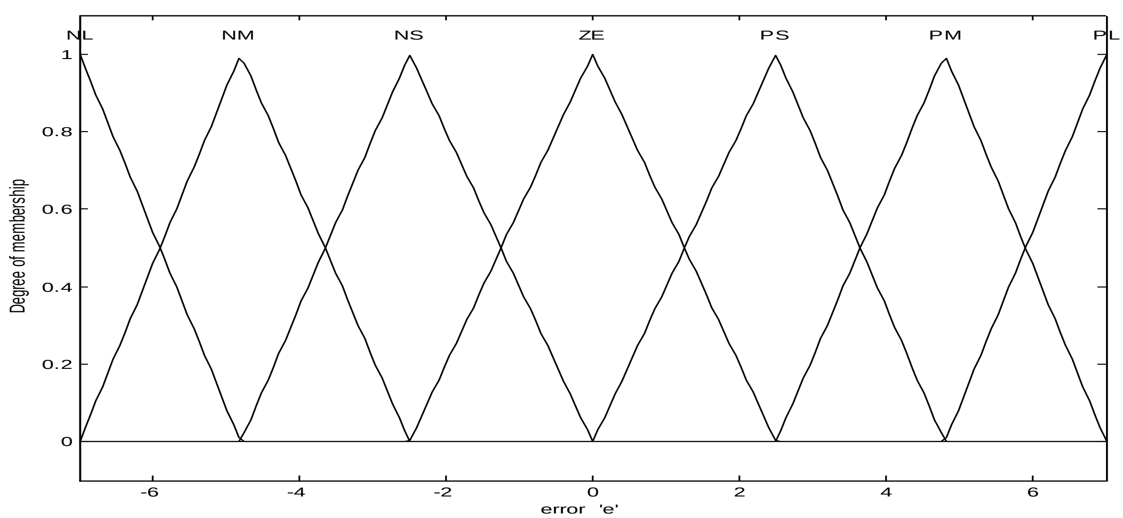

Fig.(4a) Input domain : Triangular membership functions of error ‘ e’

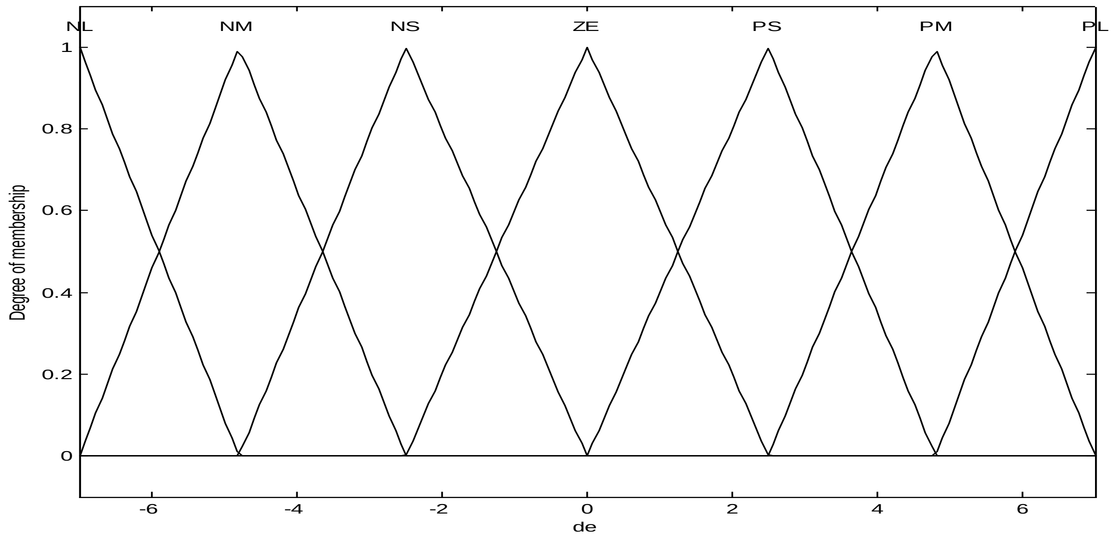

Fig.(4b) Input domain : Triangular membership functions of change in error ' δe'

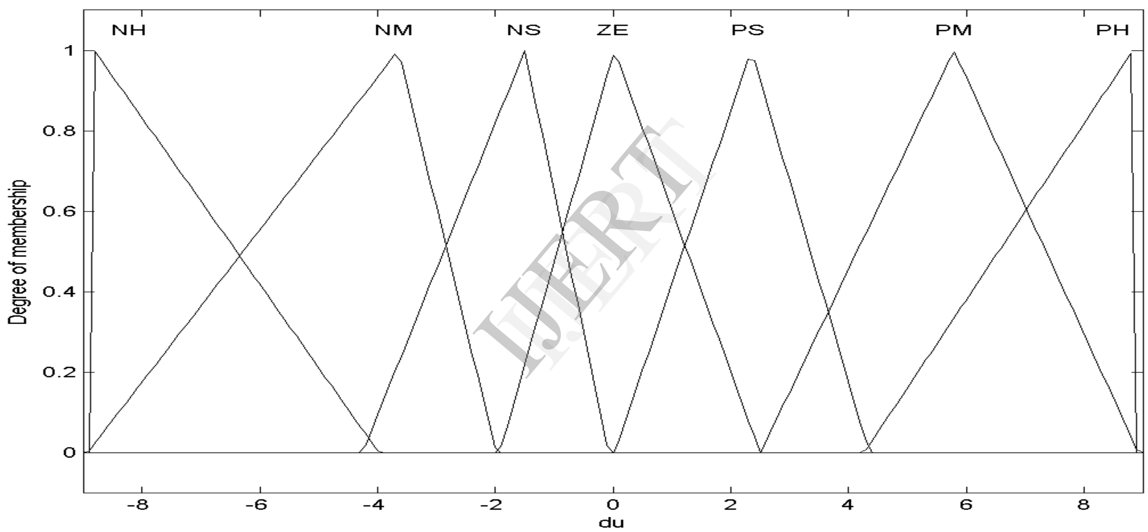

Fig. (4c) Output domain :Triangular membership functions of change in base flow rate 'δu'

This design phase of FPC incorporates the knowledge and techniques of human expertise and transforms them into fuzzy logical region or fuzzy potential well this is called knowledge representation stage.

In this section a fuzzification function is introduced for each input variables (e and δe) to accommodate the associated measurement of uncertainty exerted in pH process and to produce corresponding output.

Rule Base -

The fuzzy rule base structure has been created from the actually data accumulated during real run of pH process plant. In other words titration curve is exploited to generate the rule-base.

Figure 3 represents the behavior of the pH process in which pH value increases with increase in base flow rate in the following manner [12] –

- More the flow rate (10—65 %) smaller the increase in pH value (4 – 6.5)
- Smaller the change in the flow rate (68-78 %) greater the change in pH value (6.5–10.5)
- Larger the change in base flow (75-100 %) insignificant change in pH value

Assuming plant behaviors as predicated in the Figure 3 fuzzy IF THEN rules have been prepared. This is a complete task of operation in logical as well as physical sense. For instance, desired output of pH about 4 where error is still **Negative Large (NL)** but change in error is **Positive Small (PS)**. Therefore inference suggests that output δu must be **Negative High (NH)**. In all, maximum possible such rules may be formed using methodological sense -

- IF error in pH and change in error are observation attributes THEN change in input δu of the process is control attribute.
- IF start-up / initial phase –THEN change the input in response to the set-point change.
- IF process is not responding THEN adjust input.
- IF process is responding normally THEN keep input the same.
- IF error is zero or very small THEN take the action

In the present system two input variables (e and δe) consists of 7 and 7 different membership functions respectively, hence, possible nonconflicting fuzzy inference rules are 49. For the present system some rules are adjusted and incorporated for achieving the expected output. They are conveniently represented in the Matrix form, which is as shown in Table -2.

Table-2

Rule Matrix for Fuzzy pH Controller.

δe \ e	**NL**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PL**
NL	NH	NH	NH	NH	NH	NH	NM
NM	NH	NH	NH	NH	NH	NM	NS
NS	NH	NH	NH	NM	NM	ZE	PS
ZE	NM	NS	**ZE**	**ZE**	**ZE**	PS	PM
PS	NS	ZE	PS	PM	PM	PH	PH
PM	PS	PM	PH	PH	PH	PH	PH
PL	PM	PH	PH	PH	PH	PH	PH

Antecedent and consequent part of the process formulate the complete rule base, sample rules are listed in Table -3.

Table –3
Sample Rules

```
If (e is NL) and (de is NL) then (du is NH)
If (e is NL) and (de is ZE) then (du is NM)
If (e is NL) and (de is PL) then (du is PM)
If (e is NM) and (de is NM) then (du is NH)
If (e is NM) and (de is PL) then (du is PH)
If (e is NS) and (de is NL) then (du is NH)
If (e is NS) and (de is ZE) then (du is ZE)
If (e is NS) and (de is PL) then (du is PH)
If (e is ZE) and (de is ZE) then (du is ZE)
If (e is ZE) and (de is PL) then (du is PH)
If (e is PS) and (de is NS) then (du is NM)
If (e is PS) and (de is ZE) then (du is ZE)
If (e is PL) and (de is NL) then (du is NM)
If (e is PM) and (de is PL) then (du is PH)
If (e is PL) and (de is PL) then (du is PH)
```


Once fuzzy rules are derived, next part is its implementation known as 'fuzzy inference process'. Due to its proven practical benefits, Mamdani's method of implication has been, employed.

Defuzzificaon -

The FLPC employs Mamadani type individual rule based fuzzy logic inference. In practice a crisp value is required as final out put variable. Thus, the fuzzy consequence must be defuzzified. The purpose of the defuzzfication is to convert each conclusion obtained by the inference engine, which is expressed in terms of fuzzy set, to a single real weighted output value (crisp). Fuzzy consequence of the fuzzy reasoning is clipped fuzzy sets - $\mu(z)$. It can be defuzzifid by several different methods. The most common is the **Center of Gravity (CoG)** method. It is mathematically expressed as [13] .

$$z = \frac{\sum_{i=1}^{n} \mu(z_i) z_i}{\sum_{i=1}^{n} \mu(z_i) z} \quad .... \quad (4)$$

where, z_i are quantization points for the discretization of the output membership function $\mu(z)$ and n is the number of the quantization points

The defuzzed value is the action taken by FLPC (change in base flow). In the present system well known **CoG** method of defuzzification has been used. Resulted crisp values (output) are change in base flow δu. In actual practice **evalfis** function from FUZZY TOOLBOX (MATLLAB) used to calculate the defuzzified value based on **Center of Gravity** or **Centroid method of defuzzification (CoG)**. This process includes contribution of each fuzzy logic rule is evaluated. This process of inference computes the overall decision-outcome based on each individual rule in the rule base. In this scheme each rule individually fired by crisp value of input variable from fuzzification module and clipped fuzzy sets representing the overall fuzzy output of control steps under execution.

3. EXPERIMENTAL RESULTS AND DISCUSIION

Block diagram of overall designed and developed FLPC system is shown in Figure 5. It consists of fuzification, inference mechanism and defuzzification among pH process itself. In this scheme instead of conventional PID controller Fuzzy Controller has been used test runs

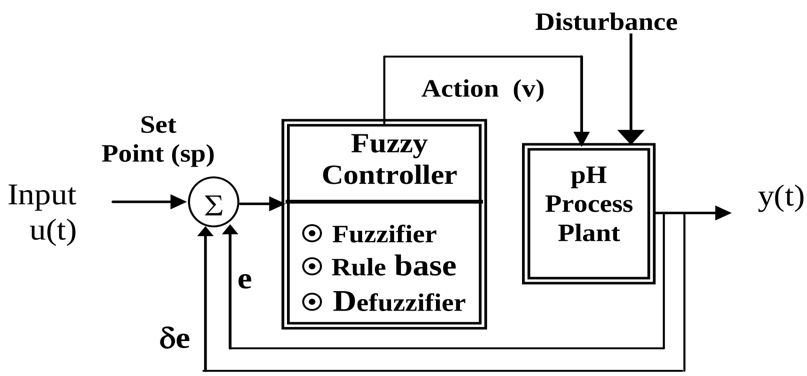

Fig. (5) : Block Diagram of Fuzzy Logic pH Controller (FLPC) Sytem.

carried for the various set points. Results and discussion have been presented in the next section.

pH process reaction is carried out in CSTR (Continuous Stirred Tank Reactor) and it is controlled by FLPC for various initial conditions and strategies of plant which are already used in PID control scheme. FLPC takes the action according to error and change in error of pH value produces corresponding output change in base flow which has bearing on value of the process and therefore, this change in controlled variable (pH) again affect on the error and change in error.

Thus, system behaves as a feedback system (closed loop) in the time varying domain (Fig. 5). Main objective is to maintain the pH constant at the desired values. In present study on line performance evaluation has been carried out using set point tracking method (Servo method). In this method a particular group of set point is defined {6.8, 7.0, 7.5, 8.4, 9.5, 8, 10, 7} and fed to the system in order to observe its behavior with respect to change of set point. The accompanied change in the base flow (NaOH) can be observed from the Figure 6.

Both controllers have been tested in the pH range 6 to 10, which is often used in pH Process Industries. From the Figure 6 comparative results of FLPC and PID with respect to some set points have been summarized in Table 4.

Table 4

Experimental results of PID and FLPC

Sr. No.	**Set Point**	**Performance Evaluation**					
		PID Optimization by Ziegler Nichols method at set point 7			**FLPC** (Optimization by design of 7x7 fuzzy matrix rule set)		
		Overshoot / undershoot	Settling time (min)	Offset	Overshoot / undershoot	Settling time (min).	Offset
1	7.0	0.1	8	Negligible	No	4	0
2	7.7	0.3	5	No	No	3	0
3	9.5	No	25	No	No	10	0

From the Table 4 following results are obtained -

- For the set point 7.0 : this set point is known as neutrality point, at this point pH process is very sensitive to control. PID controller shows no oscillation around set point and settles with no offset while FLPC shows better response with no offset, no overshoot and settles in less time and appears to be more stable than the PID.

- For the set point 7.7, the PID shows no overshoot with settling time 5 min. FLPC curve has attended desired set point smoothly without any overshoot/undershoot without any offset with 3 min. settling time.
- For set point 9.5 both, the PID and FLPC show no overshoots/undershoots. However, PID controller shows 25 large offsets and requires more settling time than FLPC.

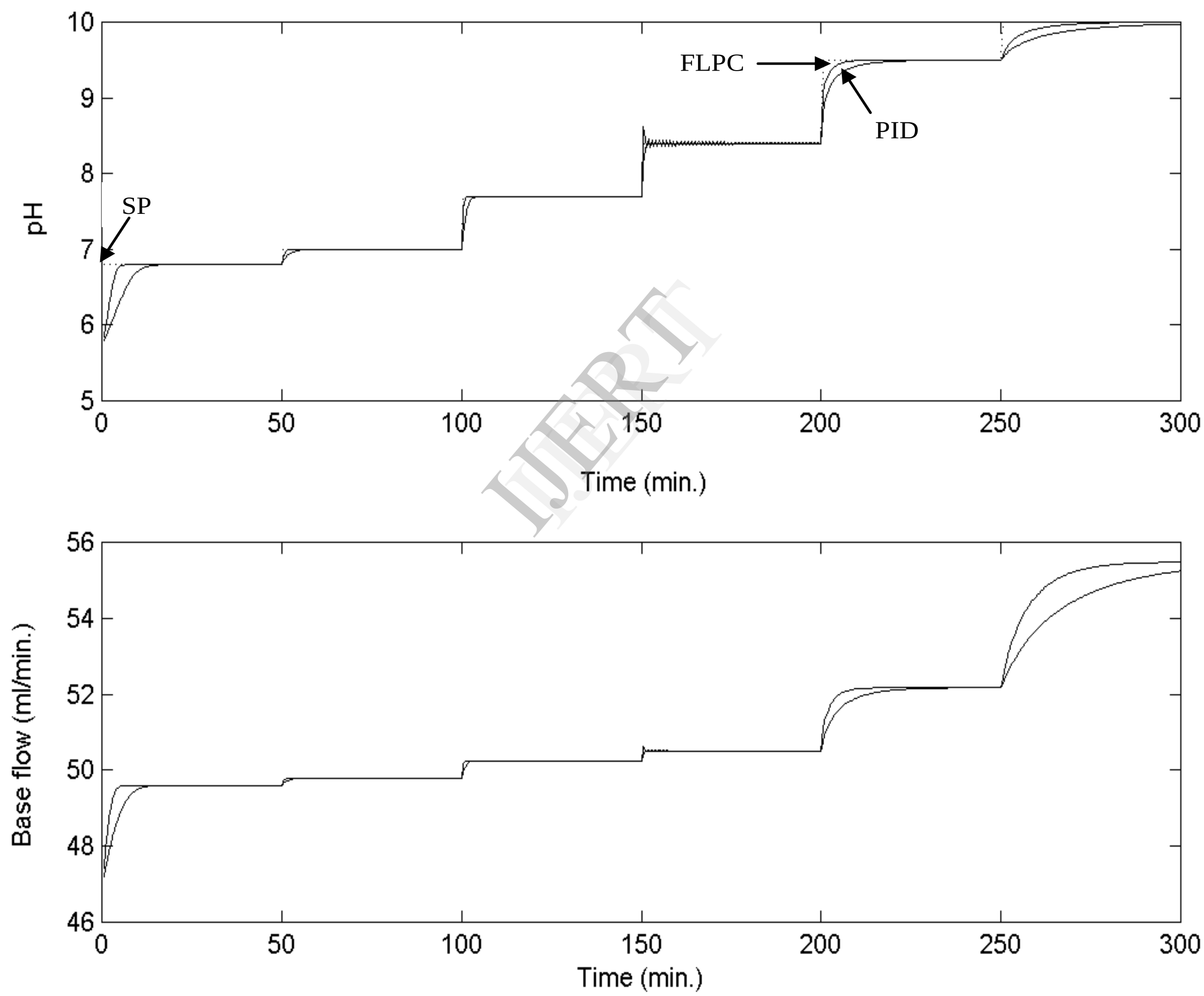

Fig.(6) Set point tracking : PID verses FLPC response

- The typical performance of FLPC for desired pH value 9.5 is as shown in Figure 7 which gives the strong support to ultimate use of fuzzy logic in control field.

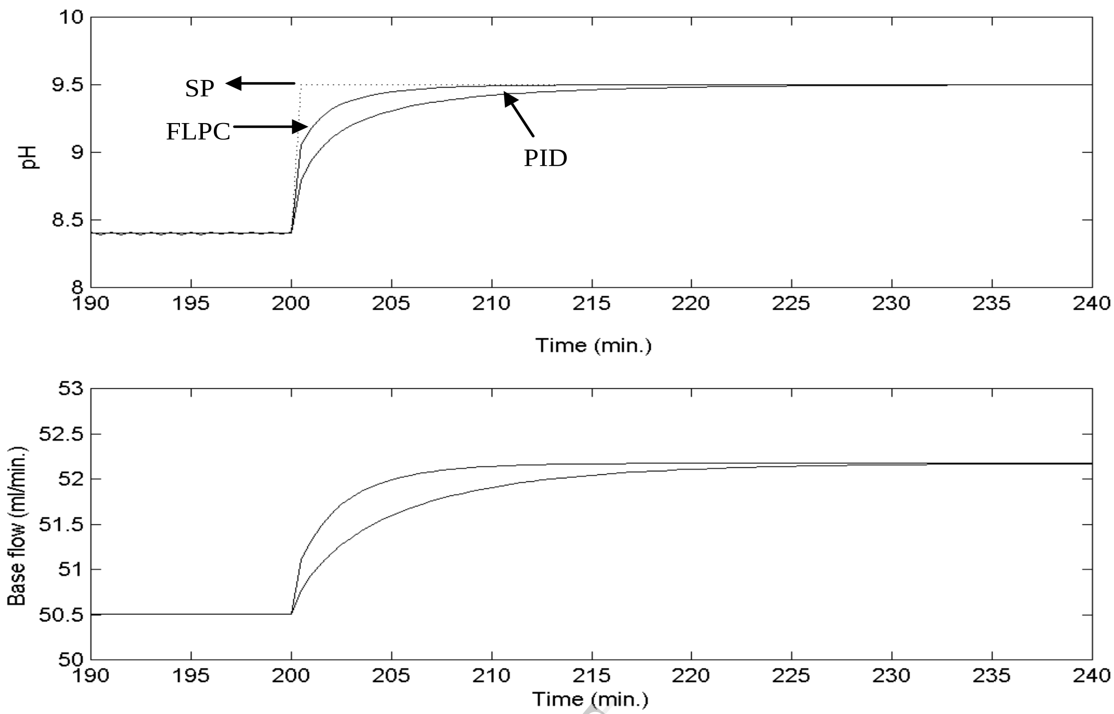

Fig. (7) Response of PID and FLPC at set point(pH) = 9.5

4. CONCLUSION

- The FLPC gives better result for large continuously changing pH process parameters.
- Most of the literature available for pH control is for strong acids and strong base or weak base and weak acid. In this communication we attempt to present the FLPC system for **weak acid and strong base, which is highly non-linear,** and hence Fuzzy Logic stand better Add –On technique to handle the nonlinearity involved in such cases.
- FLPC is an Add-On technique added to PID based pH control system. It has demonstrated satisfactory performance. The fuzzy logic employed has allowed implementing the control of pH through neutralization (pH = 7.0) in linguistic form. Handling of nonlinear dependency of pH value effectively tackled by FLPC system. Comparison with conventional PID control shows that FLPPC has smooth control even against accidental disturbances within the process. However, FLPC needs vigorous tuning of membership function for optimum pH control in the initial stages before being put through for industrial application.

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