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Research Article

Fuzzy Logic for PH Control in Wastewater Treatment in Acid-Base Neutralization Processes

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Abstract:

In an automated Water treatment plant, we monitor and control things like Temperature, Pressure, Level, Flow and Vibration. The automation industry relies heavily on Process Control. The level of detail needed in each control mechanism has risen due to unexpectedly higher requirements, instruments and control loops. Thus, a simple PID control is impossible to apply in practice to any real-time process and would not automatically work for the entire plant. An improved method of PID control for pH neutralization in a water treatment plant is suggested in this paper by incorporating Fuzzy logic. Any time a process involves many variables, this procedure can be applied.

1. Introduction

Wastewater treatment is critical for protecting environmental and public health, especially as industrial and municipal effluents continue to increase worldwide. Among the key parameters that must be strictly controlled in wastewater treatment systems is the pH level, which directly affects the effectiveness of various chemical and biological treatment stages and compliance with discharge regulations [1]. Controlling pH is inherently challenging due to the' nonlinear and time-varying nature of acid-base neutralization reactions. The system response near the neutral point (pH 7) is particularly sensitive—small additions of acid or base can result in large fluctuations in pH, making traditional control methods such as Proportional-Integral-Derivative (PID) controllers often inadequate without complex tuning or compensation strategies. In this context, fuzzy logic control (FLC) has emerged as a promising alternative. Fuzzy logic offers a rule-based framework that mimics human reasoning and decision-making, making it well-suited for systems that are difficult to model mathematically or are subject to uncertainty and nonlinear behavior [2]. Using linguistic rules and adaptive control strategies, fuzzy logic controllers can achieve robust and stable pH regulation in dynamic wastewater environments. This research aims to design, simulate, and evaluate a fuzzy logic control system for real-time pH neutralization in wastewater treatment. The study compares fuzzy logic's performance with conventional PID control, highlighting intelligent control systems' advantages and practical implications in environmental engineering applications [3].
Fuzzy logic was introduced into wastewater treatment at the start of the 2000s because it could address nonlinearity and uncertainty. The authors of the 2003 study, Meyer and Pöpel [7], were the first to introduce fuzzy logic to guide internal recirculation in wastewater treatment, which led to greater nitrogen removal and improved energy use. Fiter and his colleagues (2005) [6] used fuzzy logic control for aeration in wastewater treatment after that and noticed both energy savings and consistent quality of the wastewater effluent.
Several pilots have been set up for hybrid control strategies which use both automation and control by the pilot.
Researchers looking to combine PID control and fuzzy logic be began to introduce hybrid control systems. Chiu and Liaw (2004) [3] created a combination fuzzy-PID controller for treating industrial wastewater, showing that it brought about

better system stability and used less control effort. Naseer and Khan (2013) [8] then tested their hybrid scheme in a pH neutralization plant, using different influent conditions to show its good performance.
Fuzzy logic is being applied to more specific aspects of wastewater treatment by recent research. According to Demirci and Özbeyaz (2019) [4], a fuzzy logic controller improved the stability of electrocoagulation systems when the temperature changed. According to Alnajjar and Üçüncü (2021) [1], fuzzy models enabled biological treatment ponds to achieve greater efficiency when removing pollutants. Bhattacharjee et al. (2022) [2] used a new approach based on type-2 fuzzy logic to predict effluent quality with a strong accuracy. The Kilinto Brewery was the site for Endale's (2020) [5] practical study, where a fuzzy logic controller controlled pH neutralization of wastewater. It was found that, compared to traditional PID controllers, the system used less chemistry and was also more stable. Equally, in the case of textile wastewater treatment, Ulucan-Altuntas et al. (2021) [9] used fuzzy logic with electrocoagulation to attain high removal success for color, COD, and TOC.

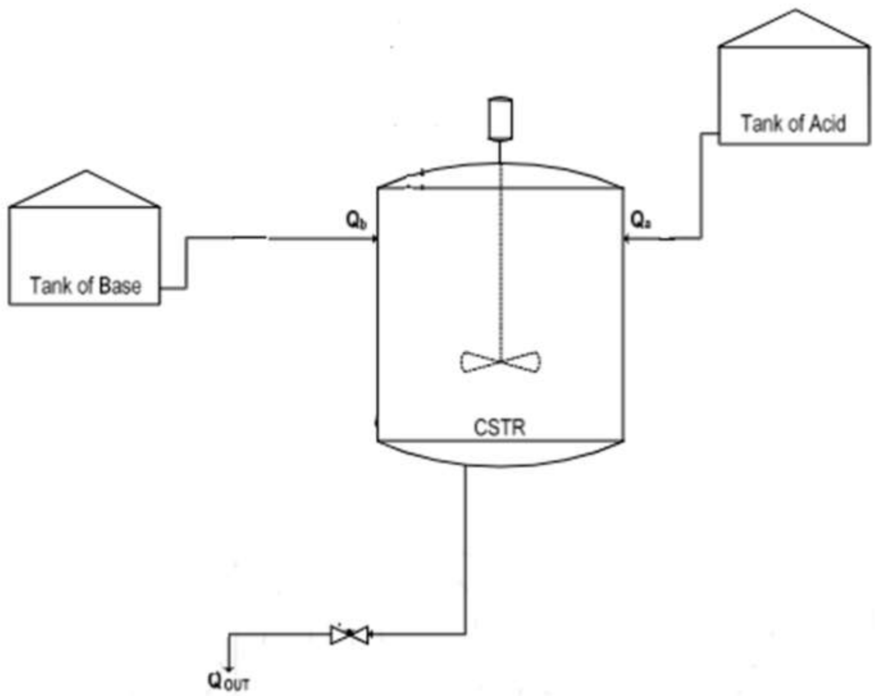

Figure 1. *pH neutralization plant*

Examination of traditional PID
Because of its simple operation and strong stability, the conventional PID control, which was first developed as control theory, has been widely applied in many different fields (Fig. 2). The PID controller's open-loop transfer function is represented by equation (1):

$$Y(S)/R(S) = K_P + K_I \, 1/S + K_D \, S \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (1)$$

The control process primarily mitigates deviation, significantly influencing the system's efficiency. When the system generates a deviation, it can promptly develop and eradicate an effect. The effect depends on how much the proportional coefficient KP is. The system's reaction velocity can be increased by increasing KP, but a too high proportional influence might jeopardize the system's stability and cause a significant overshoot. The main purpose is to eliminate the system's residuals by applying a memory effect to the mistake. The size of its corresponding coefficient KI is likewise related to the degree of its effect. There is hysteresis in the integral action. The accuracy of the system may be improved, and system residuals eliminated with the right integral action. The dynamic qualities of the system will be weakened, and control effectiveness will be compromised by excessive integral activity.

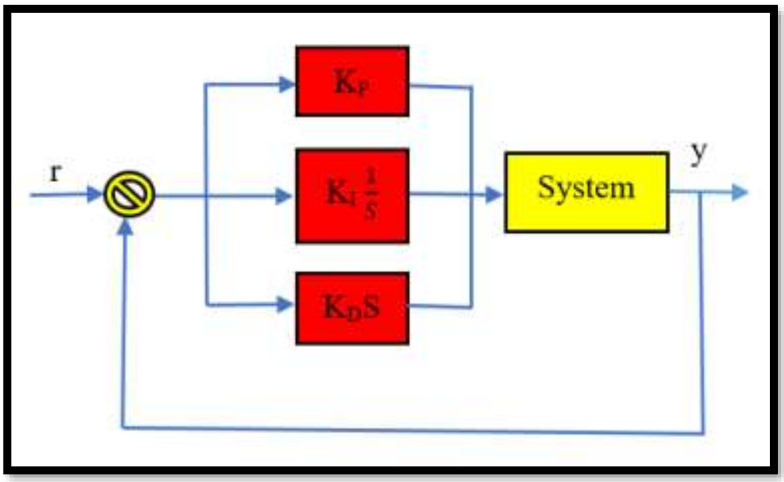

Figure 2. *Block Diagram of PID Single Loop Controlling.*

Experimental study and experience describing the relationship between the deviation e(t), the rate of change of deviation de(t)/dt, and the three parameters of the PID controller KP, KI, and KD is as follows. At the start of the reaction, e(t) is huge. Accelerating the system's response to attain the designated value promptly is essential. Subsequently, KP must be elevated to meet the requisite standards to diminish the system's response time and lower the damping coefficient. A reduced KD is essential to provide a swift response; furthermore, to prevent a substantial overshoot, the system's integral action is eliminated, namely KI = 0.In Figure 3, the system response is nearing the specified value, indicating that e(t) reaches a moderate maximum. A large KP is initially required to enhance the system's reaction; however, it must be diminished to mitigate overshoot. Additionally, KD must be appropriately calibrated

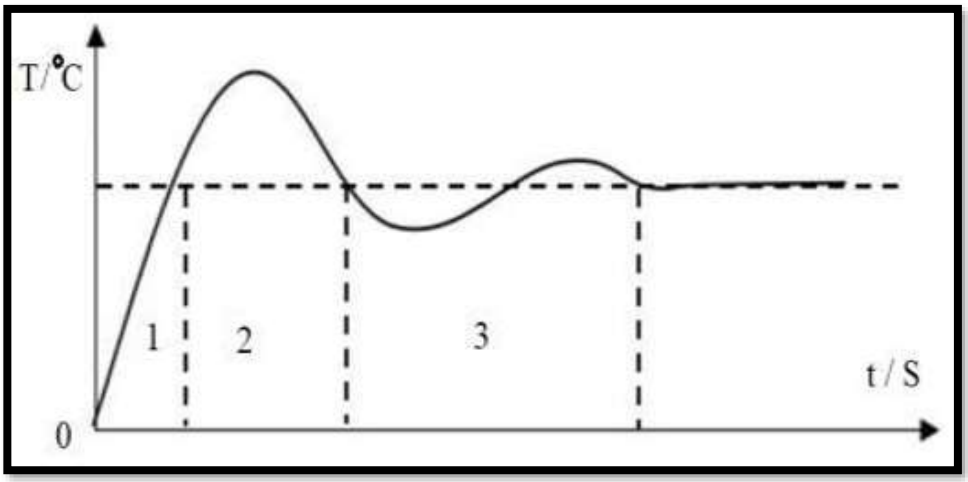

Figure 3. *Three-Phase Graph of PID Phase Response.*

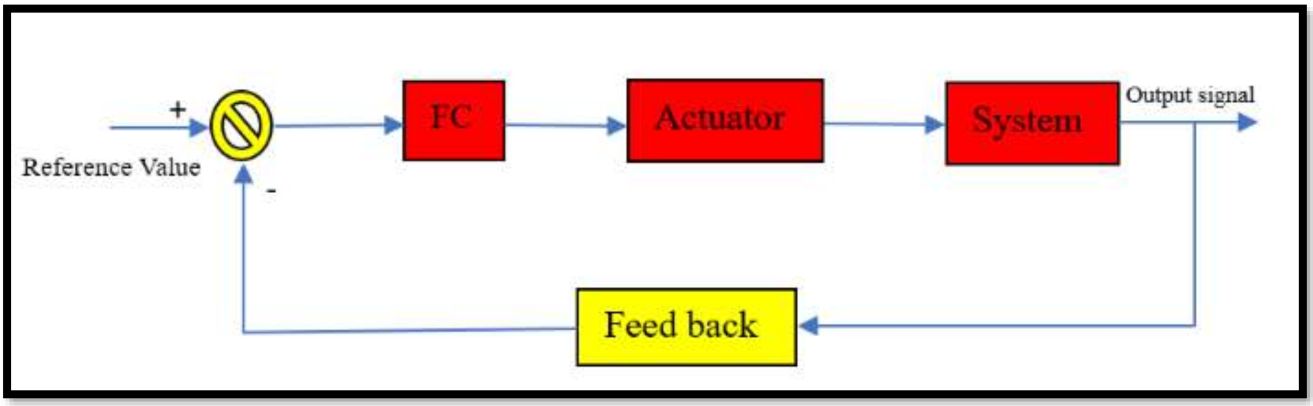

Figure 4. *Graphical illustration of fuzzy control*

to maintain system rapidity and stability. It is essential to augment the KI to reduce the residue suitably. When the system approaches stability, namely when e(t) is minimal, the system's accuracy is evaluated. Adopting bigger KP and KI values is essential to enhance the system's accuracy and mitigate oscillation while the KD value remains comparatively more minor. Figure 4 illustrates the architecture of the fuzzy control system. It diverges from the ordinary PID control by substituting the standard controller C with a fuzzy FC.A fuzzy control system is the name given to the system that contains the FC controller. FC is the basic building block of the fuzzy control system. The controller design of the fuzzy control system is different from that of the conventional PID system. Fuzzy control (FC) is applicable to fuzzy sets and focuses on making decisions based on fuzzy rules and approximate reasoning. The FC has to fuzzily each amount x1 input in order to control the controlled object. Ultimately, an accurate number is obtained from the fuzzy quantity. Below are the principles that are presented:

Fuzzification: The fuzzy controller processes the input, converting precise quantities into fuzzy quantities by classifying the membership function and the fuzzy control subset according to fuzzy control connections.

Knowledge Base: A collection of databases and control rules that have been synthesized from control experience. The rules are set by those who have direct control experience. In order to define the control, set that is made up of the control variable, the fuzzy control language is used; the database preserves relevant data, such as fuzzification, fuzzy reasoning, and defuzzification.

Fuzzy reasoning: In order to accomplish the control goal, the operator simulates human cognitive processes to choose the best control strategy within the parameters of pre-established regulations.

Defuzzification: Defuzzification is the process by which the fuzzy controller's control strategies are converted into exact values since the control object is unable to comprehend them directly. In the first step, the defined control strategy is precisely expressed inside the fuzzy subset of its output. Converting the fuzzy subset principle into a precise value that the system can comprehend is the second step. The fuzzy set is just an extension of the classical set {0,1} to the closed interval [0,1], which expresses the intermediate quantities of the two states of 0 and 1. It represents the scenario where there are an unlimited number of alternate states in the two states from 0 to 1, a state can be associated with any point. The fuzzy set is defined by Equation (2).

$$\tilde{A}:U\rightarrow[0,1],x\rightarrow\mu(x) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Ã is a fuzzy set over the domain U and μ(x) shows how much an element x belongs to the set Ã; the membership function of Ã contains x. If x is a certain element x0, $\mu\tilde{A}(x0)$ gives the membership degree of element pair fuzzy set $\tilde{A}$. A fuzzy statistical approach means using statistics on lots of experimental data to determine the law of how many subsets belong and choosing the membership function from set A that is closest to this law. Should N experiments take place and if the times μ0 is in set A are n, then n/N is the degree to which μ0 belongs to A, meaning A(μ0).

$$A(\mu_0)=n/N \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Binary Contrast Arrangement: A multitude of items organized according to a defined criterion. Subsequently, based on the ordered results and following mathematical analysis, ascertain the overall design of the coordinate system using the known quantity.

$$u_{cen}=\left(\int_u A(u)u\,du\right)/\left(\int_u A(u)\,du\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

This procedure resembles the computation of the center of gravity of a homogeneous plate. For the discrete domain U = {u1, u2, A, un}, the membership function at uj is A(uj), hence ucen can be computed as follows:

$$U_{cen}=\left(\sum_{j=1}^{n} u_j A(u_j)\right)/\left(\sum_{j=1}^{n} A(u_j)\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

This method may be used similarly to find the center of gravity of a multi-mass planar system. Although it involves some difficult arithmetic, determining the center of gravity by area is straightforward and logical. When the domain of the fuzzy set contains a large number of points, the abscissa of the mean umom of these points is utilized to characterize the fuzzy set. The maximum membership value is then selected. It is referred to as the maximum membership average-value approach.

$$U_{mom}=\left(\sum_{j=1}^{n} u_j\right)/n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Where uj is the maximum value in each set.

2. Proposed Methodology

Principles of Design

Establishing a relationship between the rate of change of deviation de(t)/dt and the divergence of the PID parameters from the controller e(t) is crucial. Nevertheless, such processes are not easily expressed mathematically which makes it hard to construct trustworthy models. Still, fuzzy control is easy to put into practice and does well in controlling the system. The PID control is made fuzzy and self-tuning. Figure 5 depicts the diagram of a fuzzy self-tuning PID control method. As per the idea, the F controller changes the PID parameters based on the output using the PID adjustment value, after getting input values of the error e(t) and its rate of change, de(t)/dt. This way, experimentalists can see important effects without having to deal with the math of the control parameters, so they do not need to calculate de(t)/dt and e(t).

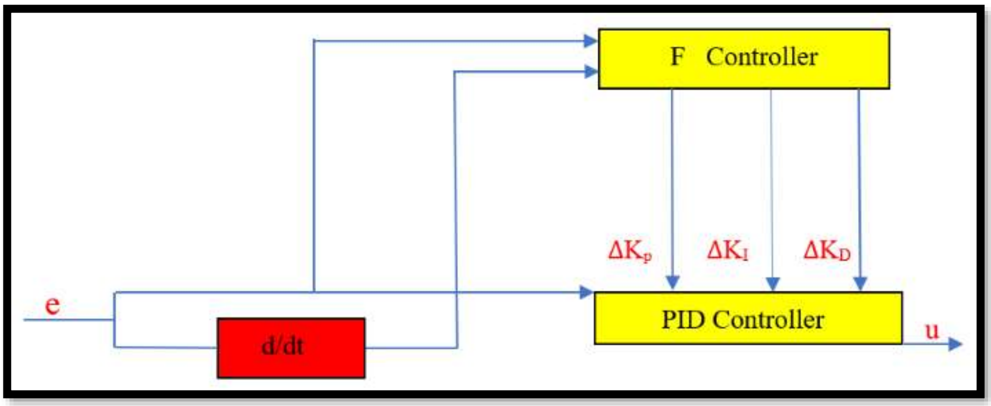

Figure 5. *Fuzzy Self-Tuning PID System Structure.*

In accordance with the design strategy, the dual control system in Figure 6 (shown by dual control block diagram for fuzzy self-tuning PID) is now replaced by a single fuzzy/self-tuning PID controller. The heart of the cascade control system is a center loop controller with two valves. Tank in Continuous or TC reactor uses fuzzy self-tuning PID control to deal with the nonlinear system. A superior level of control can be reached by using the algorithm. They are changing from the dual/valve position-cascade approach to central loop control. The PID controller changes the signal as soon as the temperature change e(t) is detected. To decide how to adjust the deviation e(t) and the rate of change de(t)/dt, the fuzzy controller use approximation reasoning. At a specific moment, the PID parameter correction value is determined and applied to each PID controller control parameter. To obtain a control result that is reasonably effective at every control stage, it modifies the controller's control performance in real time.

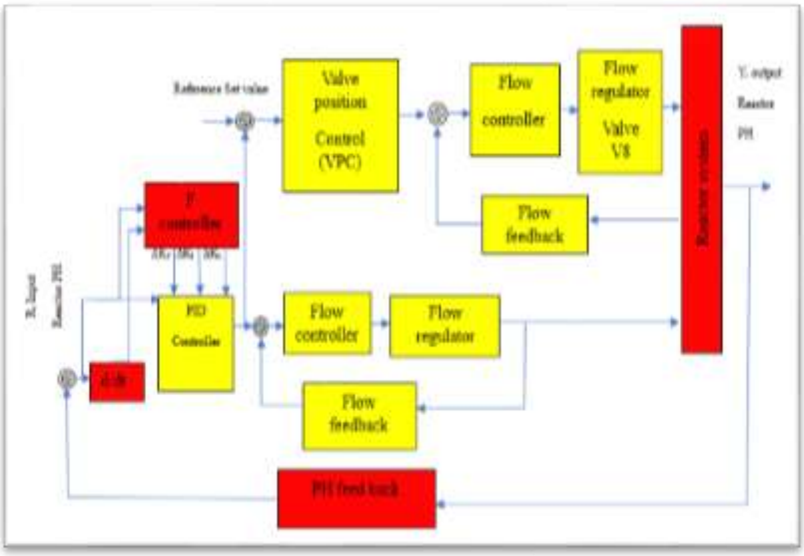

Figure 6. *Dual control block structure of fuzzy self-tuning PID.*

Choosing a fuzzy controller

Figure 7 illustrates a block design of the Mamdani-type fuzzy controller.

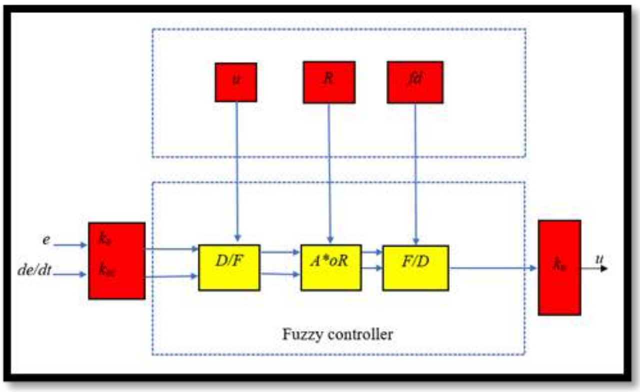

Figure 7. *Block diagram of a Mamdani fuzzy controller in two dimensions.*

D/F represents the fuzzy module, A*oR is primarily utilized for approximation reasoning, and F/D constitutes the clear module that forms the foundation of the fuzzy controller.

3. Results Of Simulation

Selection of Fuzzy Control Regulations

The fuzzy controller work within the design framework by providing the correcting values for the PID controller. From the experiments, ΔKP, ΔKI and ΔKD are set to the following fuzzy sets: (-3,-2,-1,0,1,2,3) which indicate the valve position. The main circuit of the controller is tuned via the KP, KI and KD parameters which are each mapped to the respective ranges [-20, 20], [-0.4, 0.4] and [-5, 5]. The values of kUP are 6, kUI are 2/13 and kUD are 1.

The following control rules for modifying the PID parameters may be produced by combining the aforementioned qualitative analysis with real-world operational experience and accounting for the inaccurate rate of change de(t)/dt. The fuzzy controller uses fuzzy control concepts to calculate the correction value for the PID parameter by taking into account the absolute value and magnitude of the error rate. It enables real-time parameter adjustments and has a significant effect on control. For this topic's layout, the Gaussian function of membership was selected. Figures 8 and 9 show the membership functions for the input and output.

Design of Controllers

The fuzzy pop-up controller's editing interface allows configuring two input parameters utilizing MATLAB/SIMULINK, as illustrated in Figure 10.

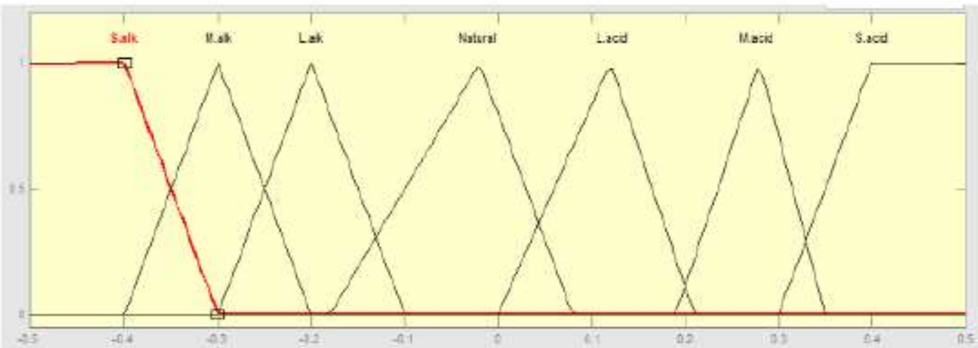

Figure 8. *An input parameter's membership.*

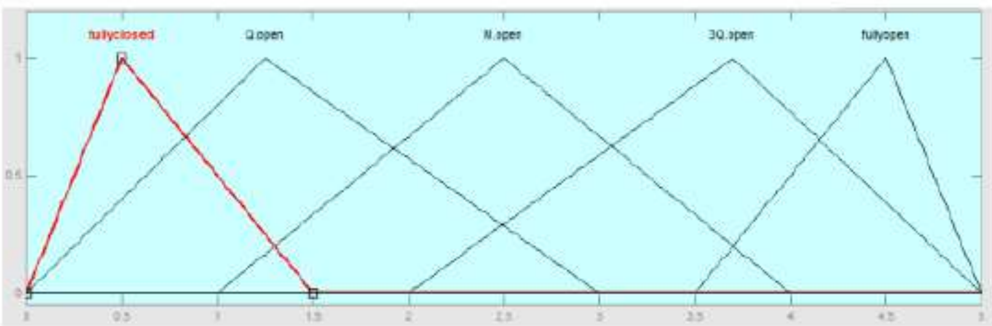

Figure 9. *Output Membership Functions*

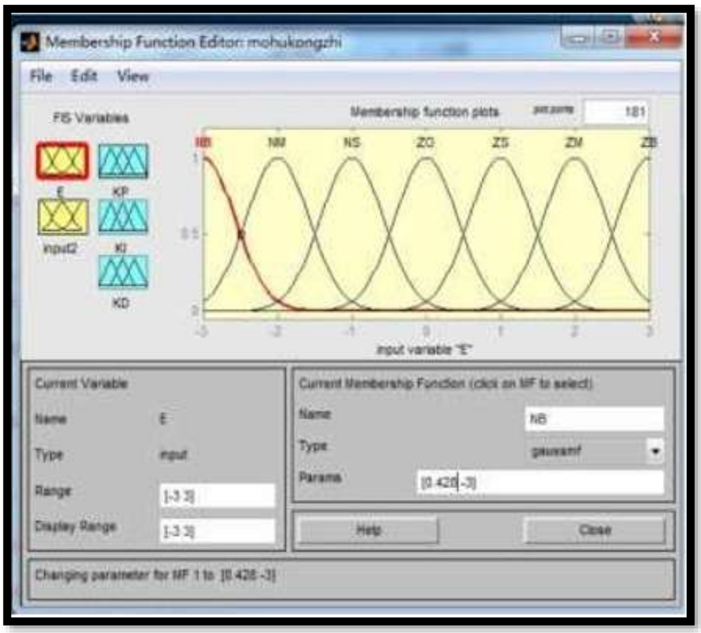

Figure 10. *The fuzzy controller's editing interface.*

The corresponding fuzzy subsets are uniformly distributed throughout the basic fuzzy domain, and Gaussian membership functions are used for the identical outputs ΔKP, ΔKI, and ΔKD. The fuzzy controller, as seen in Figure 11, operates on the basis of the fuzzy control rule, which is created in MATLAB/Simulink and is displayed in the previously described fuzzy rule control table.

***Figure 11**. Interface for editing fuzzy control rules*

Validation of the model

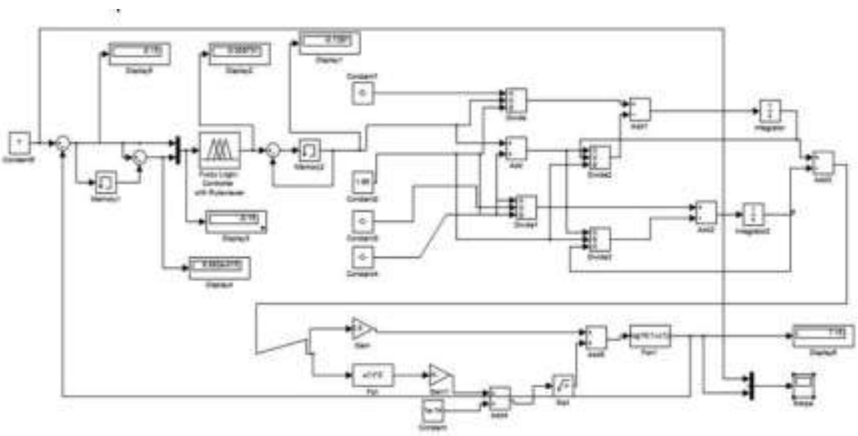

Figure 12. *Simulation software of MATLAB/Simulink, as per the design concept*

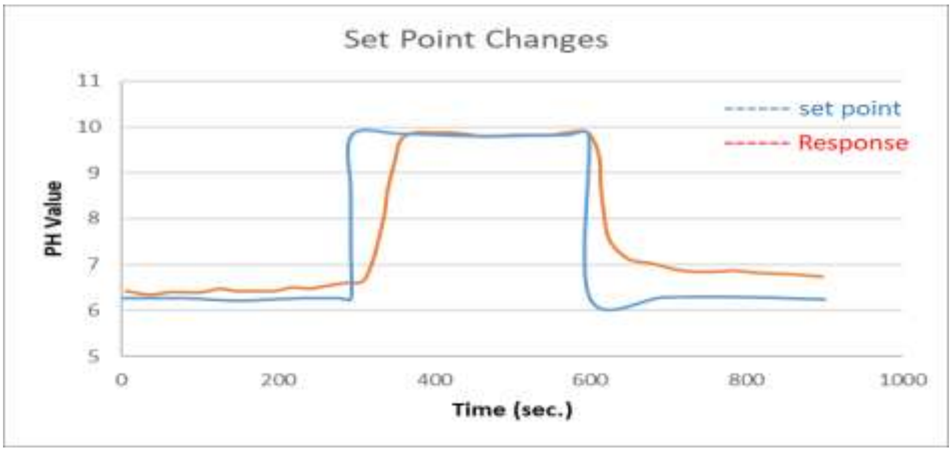

***Figure 13**. Performance of combination control mechanism*

Results:

The experiment's findings are illustrated in Fig. 12. At the start, the pH is fixed at 7 and at step 290, the input to the system becomes pH = 10. Output follows input and by time step 360 sec, the pH rises to 10. The result can be delayed since the classical PID controller's flow rate depends on the flow valves of acid and alkaline streams. It is easy to see that the output mirrors the input. Since control valves have various rise and fall times, the delays when the valve opens or closes differ.

4. Conclusion And Recommended Further Studies

The paper introduces a system that mixes a PID controller with fuzzy logic to control the pH neutralization process in a pilot plant. Potential of Hydrogen measures across the entire range of pH found in nature. One observation is that the combination controller stays more stable than the standard fuzzy logic controller. They intend to assess the proposed system by actually building and testing it in a real environment.
This paper's method is usable in all general plants that employ pH neutralization and mechanical flow meters. The strongest feature of the combination controller comes from the control valve, pH meter, flow transmitter and concentration sensors, as they are responsible for the sensor activity during design and implementation. Future plans are to make an adaptive network that could be used as a controller for the same objective.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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