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Optimization of pH Control in Acetic Acid (CH_3COOH)–Sodium Hydroxide (NaOH) Neutralization Process Using a Fuzzy Logic Controller

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Abstract

Conventional control systems, such as Proportional-Integral-Derivative (PID) controllers, have been widely applied in industrial process control due to their simple structure. However, these systems exhibit significant limitations when dealing with highly nonlinear processes and require retuning whenever plant conditions change. The pH control process represents one of the nonlinear systems in which small variations in hydrogen ion (H^+) concentration can cause substantial changes in pH values. This study develops an acetic acid (CH_3COOH) and sodium hydroxide (NaOH) titration model as a case study and designs a pH control system based on a Fuzzy Logic Controller (FLC). The proposed FLC system employs two input variables, namely error (with a membership function range of −1 to 1) and error change (Δerror) (with a membership function range of −0.5 to 0.5), along with one output variable representing valve position (with a membership function range of 4–20). Simulations were conducted at three pH set points (4, 7, and 10) to evaluate the dynamic response characteristics of the proposed control system. The simulation results demonstrate that the FLC is capable of achieving a steady-state error below 0.5% for all evaluated set points. Furthermore, the overall simulation error remains below 5%, indicating that the developed titration model provides adequate accuracy. This study confirms that FLC is an effective approach for handling nonlinear characteristics in pH control processes.

Keywords: Fuzzy Logic Control, pH Control, Acid–Base Titration

1. Introduction

pH control is one of the major challenges in chemical industrial processes, wastewater treatment, pharmaceutical manufacturing, and biotechnological applications. The success of pH regulation directly influences product quality, reaction efficiency, and compliance with environmental regulations. The fundamental challenge in pH control lies in the highly nonlinear characteristics of the titration curve, where small variations in hydrogen ion (H^+) concentration can lead to significant changes in pH values, particularly near the equivalence point [1].

Various approaches have been developed to address the nonlinear characteristics of pH neutralization processes. The Proportional-Integral-Derivative (PID) controller is the most widely implemented solution in industrial applications due to its simple structure. However, PID controllers are designed based on linearity assumptions, resulting in significant performance degradation when the operating point deviates considerably from the design condition [2], [3]. To overcome this limitation, several researchers have proposed nonlinear adaptive control approaches, including methods based on the strong acid equivalent concept and nonlinear model predictive control using Wiener models [4]. Although these approaches demonstrate improved performance compared with conventional PID controllers, their implementation requires accurate mathematical process models and intensive computational resources, limiting their application in small-scale industrial systems or systems with restricted computational capacity.

Alternatively, Fuzzy Logic Control (FLC) has emerged as an effective approach that does not require an explicit mathematical model of the controlled process. Several studies have reported that FLC can achieve superior pH control performance compared with conventional PI controllers [5]. The implementation of FLC in strong acid–strong base neutralization processes, such as HCl–NaOH systems, has demonstrated fast response characteristics, stable operation, and effective disturbance rejection capabilities.

Most previous studies have focused on strong acid–strong base systems (e.g., HCl–NaOH), which exhibit symmetric titration curves with an equivalence point precisely at pH 7. In contrast, weak acid–strong base systems, such as CH_3COOH–NaOH, possess fundamentally different characteristics: the equivalence point occurs above pH 7 due to conjugate base hydrolysis, and the titration curve exhibits a significant buffer region around pH = pK_a [6]. These characteristics introduce distinct control challenges, as the dynamic response of the system varies substantially depending on the selected set point.

This study aims to develop a mathematical model of the CH_3COOH–NaOH titration process as a representation of pH control system dynamics and to design and evaluate the performance of an FLC-based pH control system for weak acid–strong base neutralization processes. The proposed methodology involves chemical equilibrium modeling and mass balance formulation in a Continuous Stirred Tank Reactor (CSTR), the development of an FLC rule base and membership functions, and simulation using MATLAB/Simulink software. The system response characteristics, including dead time, rise time, settling time, overshoot, and steady-state error, are analyzed for each set point to quantitatively evaluate the performance of the designed controller.

2. Methods

This study employs a simulation-based approach to design and evaluate a Fuzzy Logic Control (FLC)-based pH control system for the neutralization process between acetic acid (CH_3COOH) and sodium hydroxide (NaOH). The research stages include titration process modeling, fuzzy controller design, implementation of the control system within a simulation environment, and analysis of the system response characteristics under various pH set point conditions.

2.1 Dynamic Modeling of the CH_3COOH–NaOH Titration Process

The neutralization process is modeled as a Continuous Stirred Tank Reactor (CSTR) with two inlet streams: the acetic acid (CH_3COOH) stream, which acts as a process disturbance, and the sodium hydroxide (NaOH) stream, which serves as the manipulated variable controlled by the control valve.

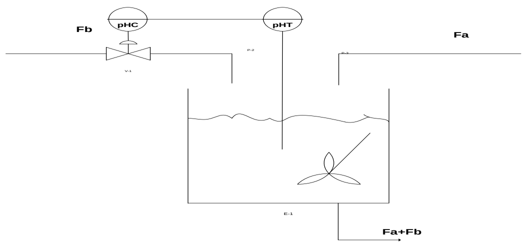

Figure 1. Continuous Stirred Tank Reactor (CSTR) [2]

The mixing process in the CSTR model is formulated under the assumptions of perfect mixing conditions, with both the ambient temperature and solution temperature considered constant, as seen in **Figure 1**. The neutralization system consists of a weak acid (CH_3COOH) and a strong base (NaOH), and the governing equations can be expressed as follows [7]:

For acid ion equilibrium:

$$\frac{V\,d[CH3COO^{-}]}{dt} = Fa[CH3COO^{-}] - (Fa + Fb)[CH3COO^{-}] \tag{1}$$

For base ion equilibrium:

$$\frac{V\,d[Na^+]}{dt} = Fb[Na^+] - (Fa + Fb)[Na^+] \tag{2}$$

Electroneutrality Equilibrium:

$$a[H^+] + [Na^+] = [CH3COO^{-n}] + b[OH^-] \tag{3}$$

Water Equilibrium at 25°C:

$$[H^+][OH^-] = K_w = 10^{-14} \tag{4}$$

Equations (1) to (4) can be combined to determine the hydrogen ion concentration ($[H^+]$) using the following equation:

$$\frac{d[H^+]}{dt} = \frac{[H^+]\{F_a[CH3COO^{-n}][H^+] - F_b[Na^+][H^+] - (F_a + F_b)(2[H^+]^2 - K_w)\}}{\{2[H^+]^2 - K_w\}V} \tag{5}$$

2.2 Fuzzy Logic Control

In this simulation, the Fuzzy Logic Control (FLC) system is designed using two input variables and one output variable. The parameters applied in the FLC design are summarized in **Figure 1**.

Table 1. Input and Output Parameter Ranges of the Fuzzy Logic Control System [5]

Membership Function	Range
Input Error	[-3 3]
Input ΔError	[-0,5 0,5]
Output Valve	[4 20]
Membership Function	Range

2.3 pH Transmitter

The pH transmitter/sensor used to measure the solution pH consists of two electrodes, where the first electrode functions as the measurement electrode and the second electrode serves as the reference electrode. Both electrodes are separated by a partition [8]. The operating principle of the pH transmitter is based on converting the detected hydrogen ion concentration (pH range of 0–14) into an electrical output signal (current range of 4–20 mA). Therefore, the gain of the pH sensor/transmitter can be determined as follows:

$$K_{pH} = \frac{span\ output}{span\ variable} \qquad 6)$$

$$K_{pH} = \frac{20\text{mA} - 4\text{mA}}{14 - 0} = \frac{16}{14} = \frac{8}{7} \qquad 7)$$

$$G_{pH} = \frac{K_{pH}}{\tau(s) + 1} \qquad 8)$$

2.4 Control Valve

A control valve is a final control element that converts the output signal from the controller into mechanical movement by opening or closing the valve position to regulate the flow rate. This action enables the process variable to be adjusted and maintained at the desired set point. The characteristic value of the control valve is formulated according to F.G. Shinskey as follows [9]:

$$f(x) = Y = \frac{x}{L + 1 - Lx} \tag{9}$$

where **Y** represents the control valve characteristic equation, **x** denotes the control valve input signal (mA), and **l** is assigned a value of one for a control valve with linear characteristics.

3.Results and Discussion

Open-loop simulations were conducted for two primary objectives: to identify the achievable set point range of the plant and to determine the most appropriate controller characteristics prior to the design of the closed-loop control system. The two input variables evaluated were the NaOH concentration (C_β) and NaOH flow rate (F_β).

3.1 Dynamic and Static Model of the Titration Process

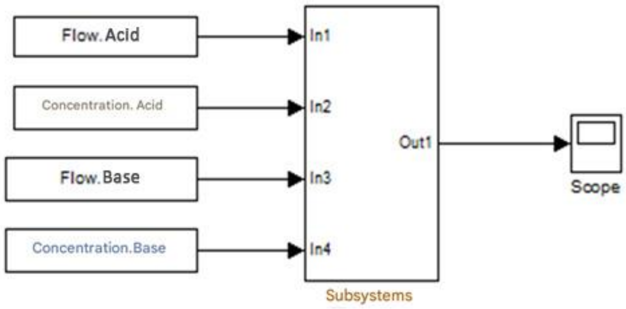

Figure 2. Open-Loop System Block Diagram

The open-loop titration simulation was performed to investigate the influence of input variables on the open-loop system response and to determine the achievable set points of the plant, as shown in **Figure 2**. In the open-loop system, two input variables (base concentration and base flow rate) were evaluated according to the specified operating range. The simulation results are presented in **Figure 3**.

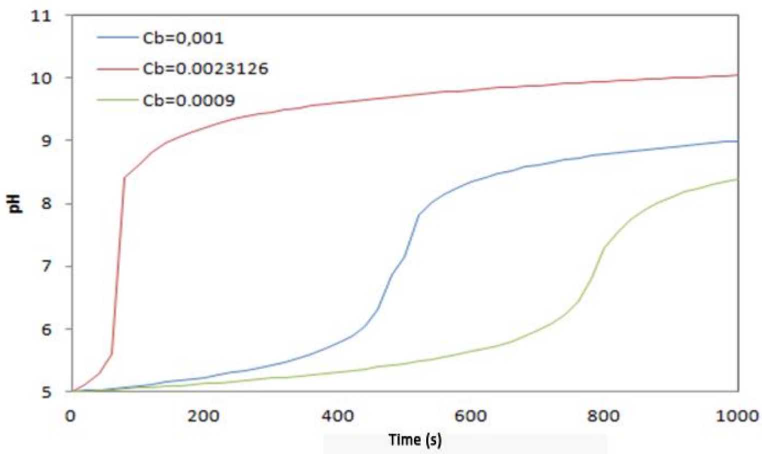

Figure 3. Effect of NaOH Concentration on Plant Output

The investigation of the effect of NaOH concentration demonstrates that C_β has a significant influence on the pH value of the plant output. At a NaOH concentration of C_β = 0.0009 M, the maximum achievable pH value was 8.38; at C_β = 0.001 M, the pH increased to 8.99; while at C_β = 0.0023026 M, the system reached a pH of 10.03. All three conditions exhibited the same minimum pH value of pH 5.

The non-proportional variation in pH response relative to changes in NaOH concentration confirms the inherent nonlinear characteristics of the titration process, considering that pH is a logarithmic function of hydrogen ion concentration ($[H^+]$). This phenomenon is consistent with the titration behavior of a weak acid–strong base system, which exhibits a buffer region around the pK_a value of CH_3COOH (≈4.76). Within this region, changes in reagent concentration produce relatively slow pH variations, followed by a rapid pH transition as the system approaches the equivalence point [10].

3.2 Effect of Control Valve Characteristics

The evaluation of control valve characteristics was conducted by comparing three types of valve characteristics: linear, quick opening (QO), and equal percentage (EP) [11]. The simulation results indicate that the linear and QO control valve characteristics provide better response performance than the EP characteristic in terms of response time, as shown in **Figure 4**. Therefore, the linear control valve characteristic was selected for the control system design, as it provides a more predictable relationship between the control signal and NaOH flow rate, thereby simplifying the development of the FLC rule base.

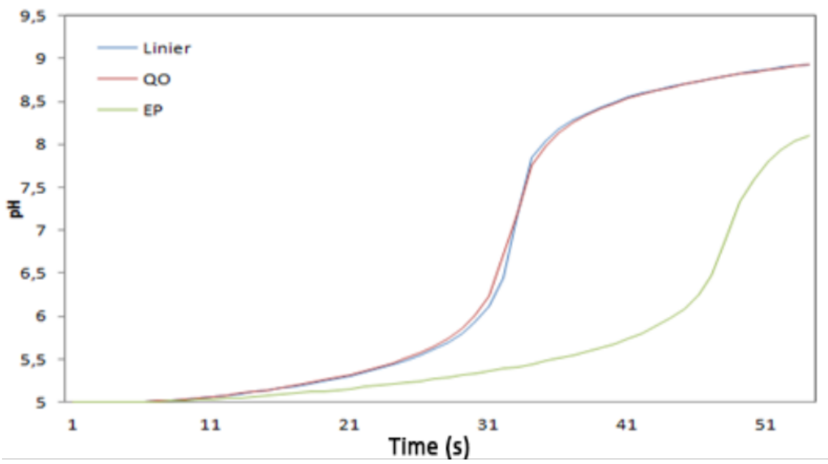

Figure 4. Effect of Control Valve Characteristics on Plant Output

3.3 Dynamic and Static Titration Model with Control Valve

A control valve was incorporated into the system to investigate the effect of NaOH flow rate on the output response. The addition of the control valve enables the influence of NaOH flow regulation on the overall system dynamics to be evaluated through simulation, as in Figure 5. The conducted simulation produced the following output response in Figure 6.

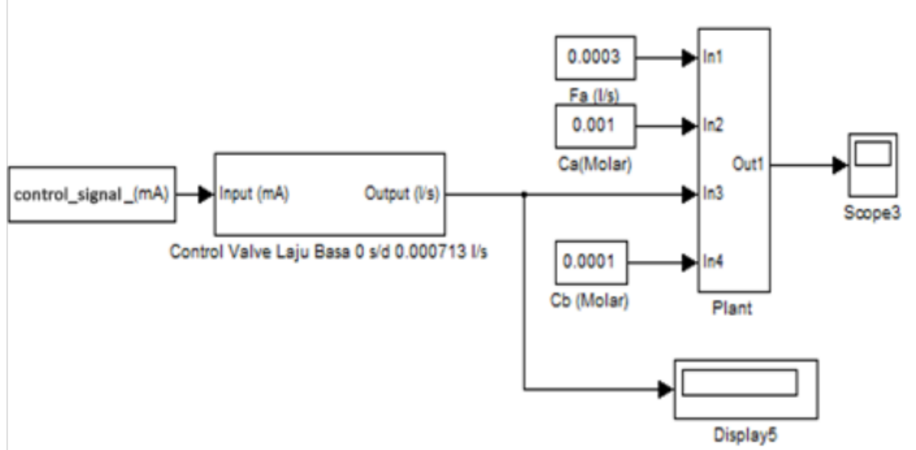

Figure 5. CSTR with an Additional Control Valve for NaOH Flow Regulation

The investigation of the effect of NaOH flow rate (F_β) demonstrates that increasing F_β reduces the time required for the titration curve to develop a sigmoid-shaped profile ("S-curve"). The resulting output pH values were within the range of pH 5–10 under all tested conditions. Based on these findings, the controllable set point range of the system was established as pH 5–10, which was subsequently used as the reference range for the design and evaluation of the closed-loop control system [12].

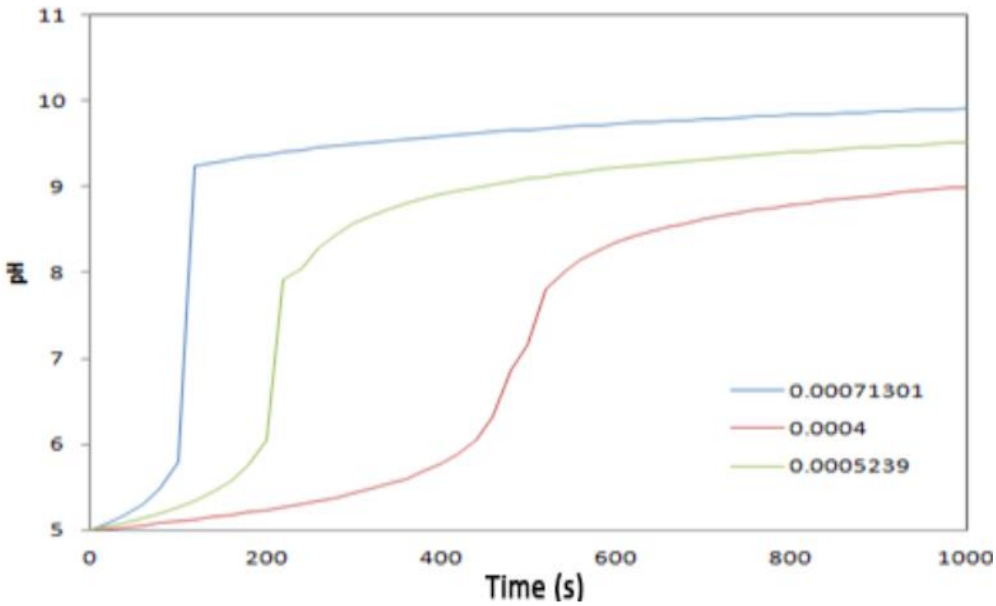

Figure 6. Effect of NaOH Flow Rate on the Titration Process

3.4 Closed-Loop Simulation

A closed-loop system is a control system that utilizes feedback from the system response as an input signal within the control block diagram. The closed-loop simulation represents the subsequent stage of the proposed control system design. The configuration of the closed-loop simulation is illustrated in Figure 7.

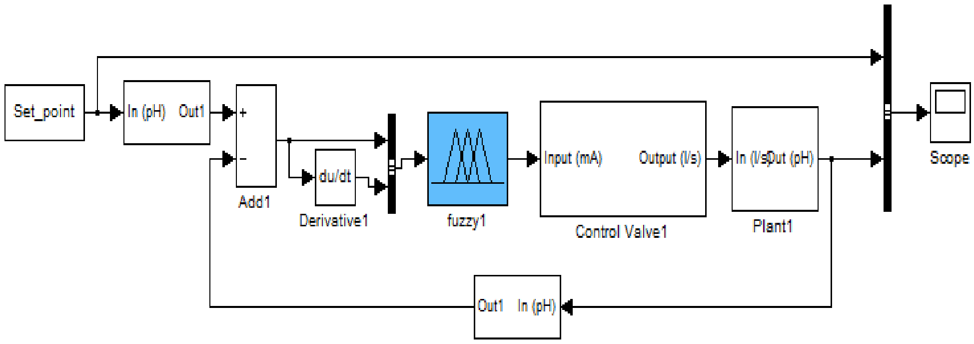

Figure 7. Closed-Loop System Block Diagram

The closed-loop system was evaluated at three representative set points, representing acidic conditions (pH 4), neutral conditions (pH 7), and alkaline conditions (pH 10). The initial system condition was set at pH 2 for all simulation scenarios [13]. The response characteristics of the system obtained from the three test conditions are summarized in **Table 2**. The closed-loop system was tested at a pH 4 set point. The system response is presented in **Figure 8**.

Table 2. Summary of Closed-Loop System Response Characteristics at Three Set Points

Parameter	pH 4	pH 7	pH 10
Dead time, td	396 s	118 s	460 s
Rise time, tr	1.268 s	78 s	462 s
Peak time, tp	—	130 s	—
Settling time, ts	1.390 s	134 s	1.332 s
Overshoot, Mp	0% without overshoot	1,4% small oscillation	0% without overshoot
Error steady-state, ess	0,50%	0,24%	0,20%

For the pH 4 set point, the system exhibited a relatively long dead time (t_a = 396 s) before the output response began to change significantly. This behavior is attributed to the fact that the pH 4 set point is below the nominal operating range identified from the open-loop simulation (pH 5–10). Consequently, the NaOH flow rate through the control valve was maintained close to zero L/s, as the controller did not apply an aggressive control action because the system only needed to maintain an acidic condition [14].

The extended rise time (t_r = 1,268 s) and settling time (t_s = 1,390 s) are consequences of this operating condition. The absence of overshoot indicates that the FLC successfully prevented excessive corrective action (overcorrection) when operating near the lower boundary of the controllable range [15]. The steady-state error of 0.50% remains within an acceptable tolerance level for industrial process control applications. The closed-loop system was subsequently tested at a pH 7 set point. The corresponding system response is presented in Figure 9.

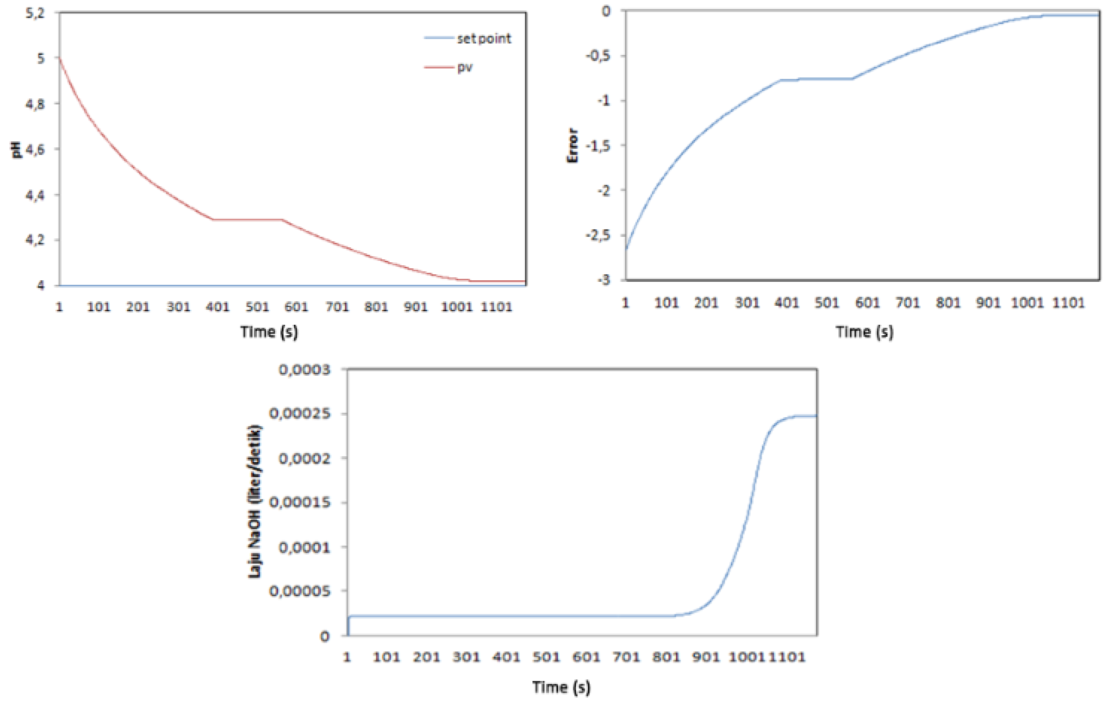

Figure 8. Closed-Loop System Response at pH 4

The closed-loop system test at the pH 7 set point produced the fastest response among the three evaluated set points, with $t_a = 118$ s, $t_r = 78$ s, $t_p = 130$ s, and $t_s = 134$ s. This rapid response can be attributed to the location of the pH 7 set point, which is close to the equivalence point of the CH_3COOH–NaOH titration process. At this region, the titration curve exhibits a steep gradient, where a small addition of NaOH results in a significant change in pH.

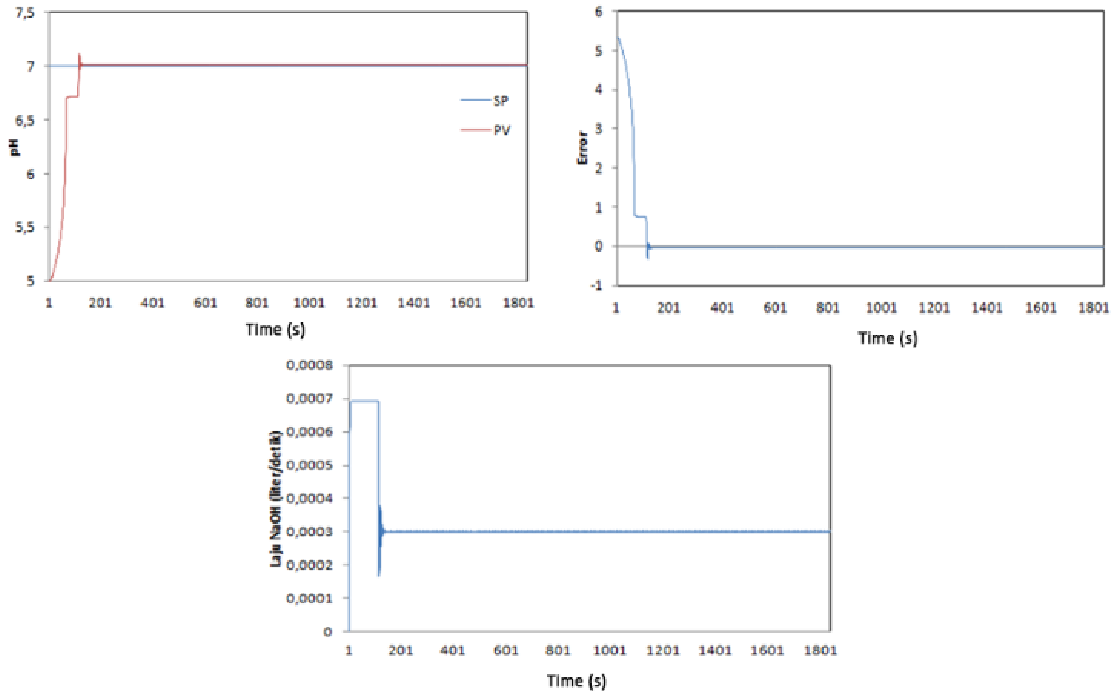

Figure 9. Closed-Loop System Response at pH 7

This condition leads to a considerably higher process gain around pH 7 compared with pH 4 and pH 10, allowing the FLC to drive the system toward the desired set point more rapidly. The observed overshoot of 1.4% is a consequence of the high process gain in this operating region; however, it remains well below the commonly accepted performance criterion of 5% for control system applications [12]. The steady-state error of 0.24% represents the second-lowest error among the evaluated conditions and indicates good system stability under neutral operating conditions. The closed-loop system was subsequently tested at a pH 10 set point. The corresponding system response is presented in **Figure 10**.

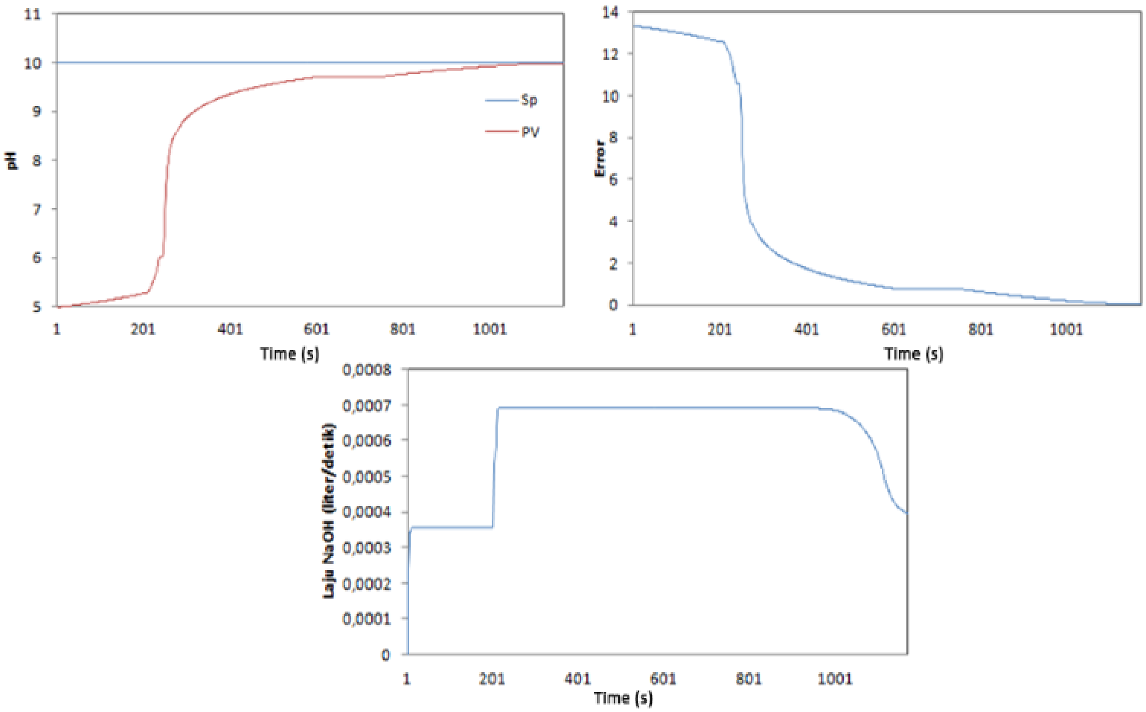

Figure 10. Closed-Loop System Response at pH 10

At the pH 10 set point, the system exhibited the longest dead time (t_a = 460 s); however, it achieved a considerably shorter rise time compared with the pH 4 set point (t_r = 462 s vs. 1,268 s). This difference reflects the distinct process dynamics at different operating regions. Under alkaline conditions beyond the equivalence point, a larger amount of NaOH addition is required, causing the system to experience a longer delay before the output response begins to change (long dead time). However, once the system response is initiated, the pH variation occurs relatively rapidly [13].

The absence of overshoot under this condition indicates that the FLC is capable of appropriately regulating the control action as the system approaches the desired set point. The controller gradually reduces the NaOH flow rate to prevent excessive base addition. The settling time (t_s = 1,332 s) and steady-state error (0.20%), which represents the best performance among all evaluated set points, demonstrate satisfactory control performance under alkaline operating conditions.

Furthermore, the developed control system implemented in MATLAB was subjected to tracking tests. Two tracking scenarios were evaluated, namely upward set point tracking and downward set point tracking. The simulation results are presented in **Figure 11**. The response obtained from the downward tracking test is presented in **Figure 12**.

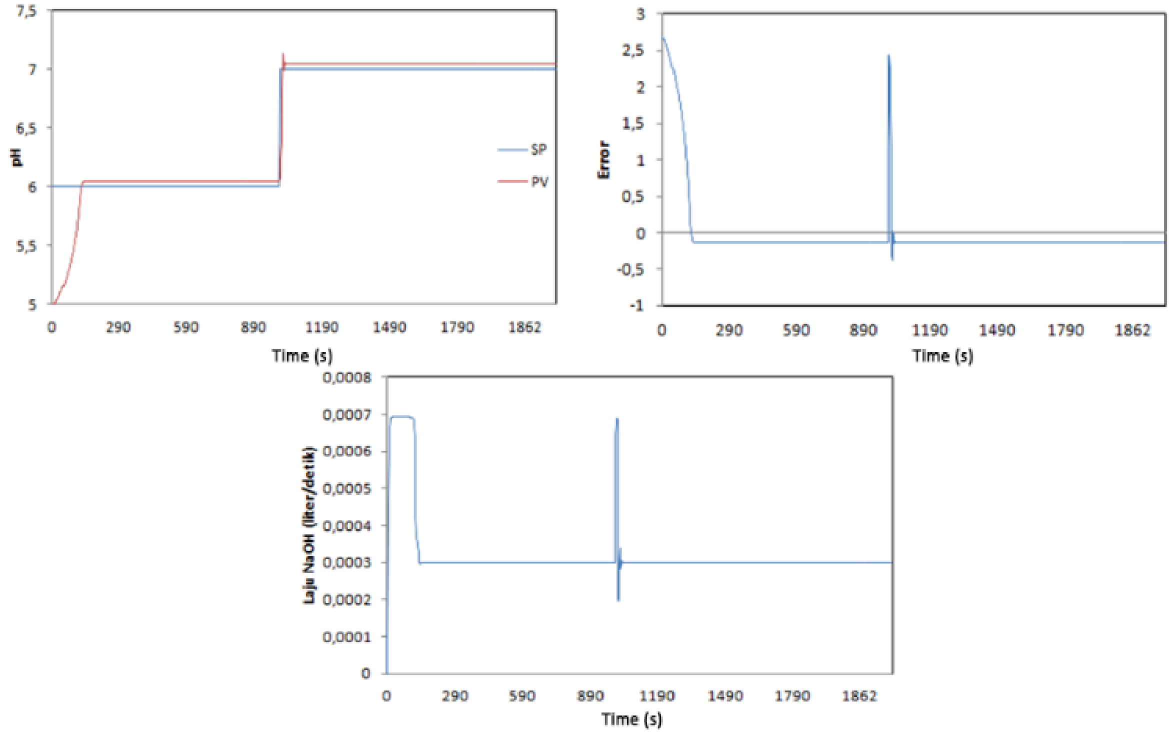

Figure 11. Upward Tracking Test Response

The upward tracking test results demonstrate that the NaOH flow rate through the control valve responds effectively to each set point variation. The temporary increase in error immediately after a set point change represents an expected transient response, as the system requires a certain amount of time to adjust the control action to the new operating condition. The error value decreases monotonically and approaches zero within approximately 100 s after each set point transition, indicating good recovery capability of the control system.

A similar response pattern was observed in the downward tracking test, where the FLC successfully reduced the NaOH flow rate rapidly and in a controlled manner when the set point was decreased. The bidirectional tracking capability confirms that the designed FLC rule base exhibits symmetrical characteristics and can effectively handle both positive and negative error conditions [10].

Several aspects should be considered when interpreting these results. First, all evaluations were conducted under disturbance-free conditions; therefore, the robustness of the FLC against external disturbances, such as sudden variations in the concentration or flow rate of the incoming acetic acid stream, has not yet been assessed [13]. Second, the model parameters were established under an operating temperature condition of 25 °C; variations in operating temperature may affect the K_a value of CH_3COOH and consequently alter the characteristics of the titration curve. Third, practical implementation in a real process system requires pH sensor calibration and further validation using experimental data. These limitations provide opportunities for future research to develop a more robust control system capable of maintaining performance under varying operating conditions and process disturbances.

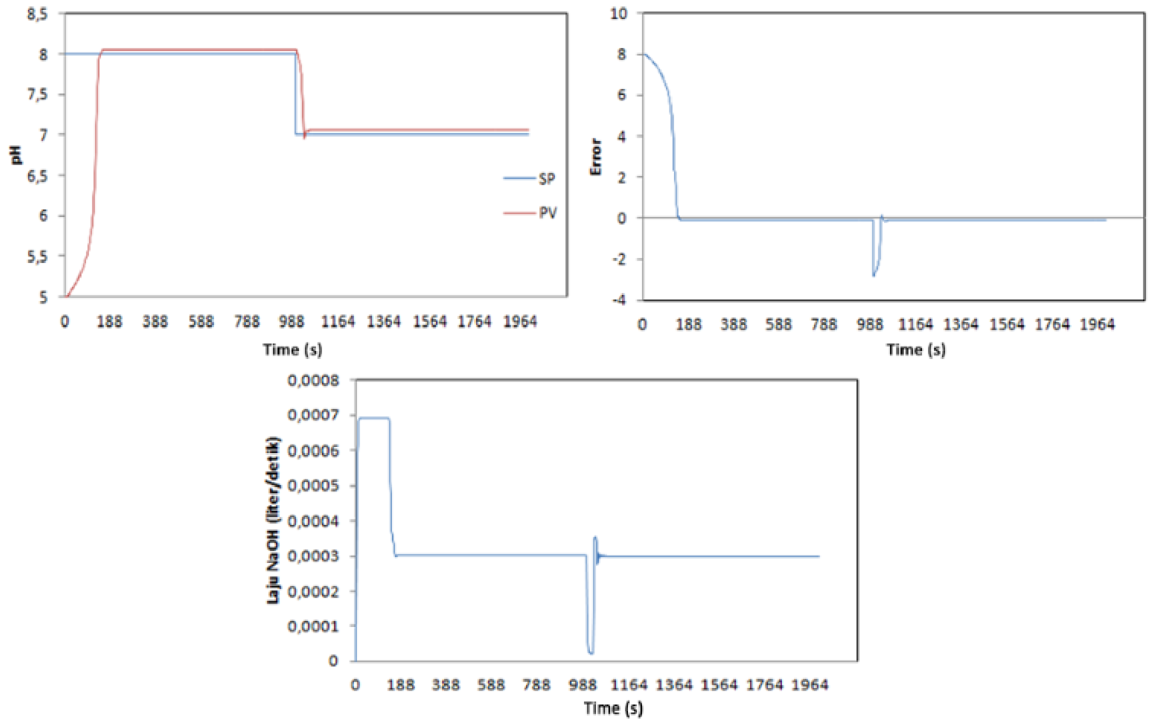

Figure 12. Downward Tracking Test Response

4. Conclusion

This study successfully developed a Fuzzy Logic Control (FLC)-based pH control system for the CH_3COOH–NaOH neutralization process using a two-input configuration (error with a range of ±1 and Δerror with a range of ±0.5) and a single output variable representing valve position (4–20 mA). The open-loop simulation established the controllable pH set point range of 5–10 and identified the linear control valve characteristic as the most suitable configuration for the proposed control system. The closed-loop simulation conducted at three representative set points (pH 4, 7, and 10) demonstrated that the FLC effectively regulated the pH process, achieving a steady-state error below 0.50% and an overall simulation error below 5%, without requiring parameter retuning under different operating conditions. Furthermore, the upward and downward tracking tests confirmed the capability of the proposed system to adapt dynamically to set point variations, with a recovery time of approximately 100 s. These results demonstrate that FLC provides an effective control strategy for addressing the inherent nonlinear characteristics of pH regulation in weak acid–strong base neutralization processes.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

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