



ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

Modeling and Control of Wastewater Treatment PH Neutralization Process Using
Fuzzy Logic Controller: Case Study of Kilinto Brewery Industry, Ethiopia

A Thesis Submitted to the School of Graduate Studies, Addis Ababa Institute
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Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification.

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This thesis has been submitted for examination with my approval as a university advisor.

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Abstract

Industrial waste water is the aqueous discard that results from the use of water in an industrial manufacturing process or the cleaning activities that take place along the process. Waste water treatment can involve physical, chemical or biological processes or combinations of these processes depending on the required outflow standards. Specifically, chemical process wastewater treatment involves pH neutralization.

Wastewater pH neutralization plays an important part in a wastewater treatment process. It is the most important characteristics of waste water treatment and is used to properly control pH value between pH 6.5 and 7.5 which, provides the optimum environment for microorganism activity. However, it is difficult to control a pH process with adequate performance point due to its nonlinearities, time-varying properties and sensitivity to small disturbances behavior of the wastewater when working near the set point.

In this thesis, a fuzzy logic based pH control system has been investigated. The first aspect of the research deals with the development of a mathematical model of a specific Wastewater pH neutralization process. It was intended that this model provide an opportunity for the development, implementation, and evaluation of both the conventional (PID) and an advanced fuzzy logic controller with the feedback control approach. In the second part, the design and simulation of the controller is dealt.

The MATLAB simulation results were used to evaluate and compare the performance of both the controllers (PID controller and fuzzy logic controller). The effluent that is discharged from kilinto brewery to the environment had a PH variation of 5.8-9. The fuzzy logic controller reduces the ISE by almost 31.3% in average. However FLC again outperforms PID by reducing maximum overshoot by 55.6%. Finally the FLC reduces the settling time by 14.37% in comparison with PID controller in average. The variation of PH is between 6.67 and 7.16 when taking pH value 7 as the set point. Thus, the fuzzy logic controller is able to provide extremely encouraging control performance in terms of tracking, handling different types of disturbance and robustness compared with a conventional PID controller.

Key words: *wastewater pH neutralization, mathematical modelling and fuzzy logic controller*

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List of Acronyms

FLC	Fuzzy Logic Control
PID	Proportional plus Integral plus Derivative
PI	Proportional plus Integral
DCS	Distributed Control System
CSTR	Continuous Stirred Tank Reactor
ISE	Integral Square Error
CH ₃ COOH	Acetate acid
NaOH	Sodium Hydrochloride
WWTP	Wastewater Treatment Plant
m ³ /s	cubic meter per second
m ³ /h	cubic meter per hour
Mhl/y	Million hectoliter per year
Kg.m ³	Kilogram per cubic meter
v	volume
UASB	Up flow anaerobic sludge blanket
COD	Chemical oxygen demand
BOD	Biological oxygen demand

1. INTRODUCTION

1.1 Background

Waste water is a big concern in environmental safety. Industrial waste water is the aqueous discard that results from the use of water in an industrial manufacturing process or the cleaning activities that take place along that process. Acidic or basic waste water is extremely dangerous. Long-term exposure to acidic or basic environment can cause illness and unhealthy life to living creatures in the world. It could cause mutation to human cells, which is usually called cancer in general term. As revealed in literature survey by Metcalf and Eddy, it is estimated that about 3-10 liters of water is required to produce 1 liter of beer [1]. As a result, a large quantity of wastewater is produced. Consequently, water and wastewater management in breweries remains a critical practical problem.

Kilinto brewery industry was established in 2013 in Addis Ababa at a kaki kality. The brewery industry had connected to the municipal sewage system with, a maximum wastewater discharge of 3.8 hl wastewater/hl beer or Maximal wastewater quantity for phase one $1,900 \text{ m}^3/\text{day}$ ($80 \text{ m}^3/\text{h}$) [2].

The principal objective of any wastewater treatment is generally to allow industrial effluents to be disposed of without danger to human health or unacceptable damage to the natural environment. Basically, wastewater treatment methods can be divided into three categories which are physical, chemical and biological wastewater treatment processes [2]. For almost all combinations of requirements in terms of effluent quality, land availability, construction and running costs, mechanization level and operational simplicity there will be one or more suitable treatment processes.

In chemical process technique, Value of pH is one of the waste water parameters that need to be controlled. PH control plays an important role in many industrial process applications such as wastewater treatment in paper and pulp plants, boiler feed water treatment in thermal power plants, biopharmaceutical plants, food processing plants, and various other chemical processing plants [2].

In chemical industry waste water treatment, the control of pH (the concentration of hydrogen ions) is a well-known problem that presents difficulties due to large variations in process dynamics and the static nonlinearity between pH and concentration.

In recent years the industrial application of advanced pH control techniques for the process industries has become more demanding, mainly due to the increasing complexity of the processes as well as due to stringent requirements of product quality and conformance with strict environmental and safety regulations [3]. Therefore the process industries require more reliable, accurate, robust, and efficient pH control systems for good operation of process plants. In order to fulfill the above requirements there is a continuing need for research to develop advanced pH control schemes. However, it is difficult to control a pH process with adequate performance point due to its nonlinearities, time-varying properties and sensitivity to small disturbances when working near the equilibrium point. The study of nonlinear systems is a complex problem since each nonlinear system exhibits its own characteristics and there is no theory that can be universally applied. For these reasons, pH control is often regarded as a benchmark for modeling and control of highly nonlinear processes. To meet these demands new trend in advanced control technology is increasingly towards the use of a control approach known as fuzzy logic control strategy rather than conventional controller [3, 4].

The main idea of the thesis is to model and control the flow rate of acid liquid and alkali liquid into the mix tank to maintain the mix tank at a specific PH values by using fuzzy logic controller. Depending on the pH value of the solution sensed by pH sensor, acid or base is added to the solution to obtain neutralized solution. After sensed the wastewater pH value in the mix tank, the system will calculate the concentration (M) based on the pH value. If the pH value is 7, then no acid or base will be pumped into the mix tank but if it is less or more than 7, then it will calculate again the concentration value so that a specific amount of acid or base will be added.

In general terms this research study can be divided into two main activities. The first of these involves pH process model development and the second is control mechanism design.

The models are designed and implemented numerically with MATLAB/SIMULINK to obtain the optimum design for the neutralization process under study. The second activity involves controller design and development, including preliminary controller evaluation using simulation. The key objective has been to develop an advanced control strategy that can provide accurate, efficient and flexible operation of the particular PH neutralization process plant.

1.2 Statement of problem

Process plants generate a wastewater effluent that must be neutralized prior to discharge or reuse. Wastewater reuse is being increasingly promoted as a strategy for conservation of limited resources of freshwater and as a mean of safeguarding the aquatic environment from contaminants present in wastewater. Waste water disposed of in the ground reduces the quality of ground water and surface waters. Therefore, pH control is needed in just about every process plant, and yet a large percentage of PH control performs poorly.

The pH control of neutralization processes is a very difficult problem encountered in the industry which need neutralization. Most of the available pH control is for strong acids and strong base or weak base and weak acid. However pH control in system for weak acid and strong base, or strong acid and weak base which is highly non-linear. The pH neutralization process is considered as highly nonlinear and time varying process, hence cannot be controlled efficiently using conventional controllers (PI and PID). On the other hand most of process plants use linear control analysis and design tools often fail to provide an effective control. To solve this problem, control of pH neutralization process using fuzzy logic controller which can provide optimized solution is necessary. Fuzzy logic system is a controller which can be applied for linear and nonlinear systems and is capable of providing optimized solution Fuzzy logic is capable of producing accurate and reliable solution from imprecise or vague information. Hence fuzzy logic is able to resemble human decision making process.

1.3 Research Objectives

1.3.1 General objective

The main objective of this thesis is Modelling and control of wastewater treatment pH neutralization process using fuzzy logic controller to maintain acceptable PH level.

1.3.2 Specific objectives

- ⇒ To provide an adequate dynamic nonlinear pH neutralization model in semi Batch CSTR, based on physical and chemical principles that can represent the real pH neutralization plant.
- ⇒ To design and implement PID controller to obtain a neutral pH for the wastewater treatment plant using MAT LAB software.

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- ⇒ To design and implement fuzzy logic controller to obtain a neutral pH for the wastewater treatment plant using MATLAB software.
 - ⇒ Investigation and evaluation of the performance (e.g. accuracy, dynamic response etc.) of a developed simulation model of the wastewater treatment under conventional PID controller and fuzzy logic controller.
 - ⇒ Detailed comparisons between the developed model under the conventional PID controller and fuzzy logic controller.

1.4 Significance of the Research

The control of pH arises in a wide range of industries including wastewater treatment, biotechnology, pharmaceuticals and chemical processing. The general aim in this form of control is to maintain the pH value within a liquid at a specific level. This can be important in order to comply with and satisfy certain environmental requirements or quality standards.

The importance of the thesis is to develop a high technology intelligent fuzzy based monitoring, and automated controlling wastewater treatment plant.

Besides that, the fuzzy logic based wastewater treatment plant can also use to replace the PID based wastewater treatment plant because fuzzy logic based wastewater treatment plant is much better compared to PID based wastewater treatment plant in the sense that fuzzy logic based wastewater treatment plant is able to overcome nonlinear control problems, well suited to low-cost implementations and can be easily upgraded by adding new rules to improve performance or add new features.

1.5 The Scope of the thesis

The present work is carried out to study the dynamic behavior of a pH neutralization process and process control by simulation with MATLAB. The goal of this investigation is an assessment of the most relevant factors that influence the pH, and of their quantitative relationships. The results of this and further research may lead to prediction of the pH of the effluent and of the possibility of biological purification of strongly alkaline waste waters.

Models are proposed for the calculation of the probable pH of the effluent for weakly, moderately and strongly alkaline influents.

1.6 Outline of the Thesis

This chapter introduces background information relevant to the thesis. It also highlights the main issues that drive this research study. The thesis problem of statement with the objectives of the thesis and the significance of the work and the proposed design solutions are presented.

The Chapter 2, deals with the main concepts and the background of the thesis and the literature survey which has been conducted about PH neutralization. It contains coverage of the main established concepts and techniques published in the literature concerning pH process modelling and control.

In Chapter 3, the overall system Architecture and a system model of that system is carried out by deriving the mathematical model in terms of the various system parameters Used in this thesis is described in detail.

In Chapter 4, the main concepts and design of control techniques conventional PID and Fuzzy logic Controllers are discussed. In these chapter deals with the design of Fuzzy logic control structure and the development of fuzzy interface system (flow rate control and PH control) are discussed.

In Chapter 5, the result and analysis of the simulated result outcome are presented. The dynamic behavior of the open loop and the closed loop controllers the performance is compared by obtaining the simulation responses.

In Chapter 6, the conclusion drawn from the gained result remarks relating to the objectives of the Thesis concerning the performance of the control of pH neutralization model and suggestions for further research are made.

2. LITERATURES REVIEW

This chapter summarizes the basic concepts and literature survey that was conducted as part of the Research reported in this thesis. It covers pertinent established concepts and Techniques published in the literature concerning pH process modelling and control.

2.1. Introduction

The control of pH is industrially important. Examples of its importance include wastewater neutralization and desalination processes. The pH value of industry waste water has to be fixed at harmless values before disposed to the environment. However, the dynamics of pH processes are highly nonlinear. This makes its control a difficult task. In addition, the concentration of the chemical species in the system can be totally or partially unknown. Improving the performance of the process through feedback control of its pH value will directly affect both the economics and the safe operation of the process. This is because good controller design will generally result in:

- ↻ Safe operation through maintaining the operational and physical constraints.
- ↻ Less operator intervention since the modern controller is fully automated.
- ↻ Higher product quality or at least fixed at desired value
- ↻ Higher yield or at least fixed at desired value.
- ↻ Products with less variability in the impurities in the product.

Bearing in mind the importance of pH control and its effect on various process industry and/or utilities in the kingdom, it is of good potential to conduct a profound investigation of the control problem of pH neutralization systems. Specifically, the investigation concentrates on experimental evaluation of process control systems on the neutralization problem of pH value in a stirred tank reactor (CSTR). Therefore, this work involves designing and building pH neutralization CSTR with its control loop accessory, designing and implementing appropriate control algorithms, and evaluation of the controller performance.

2.2. The definition of pH

PH is a measurement of the acidity or basicity of a mixture or solution. The pH range is from 0 meaning most acidic to 14 meaning most basic [1]. A pH measurement is the representation of the number of hydrogen ions in solution. A logarithmic scale is used to measure pH. The scale works in increments of 10 times more hydrogen ions then that of the previous increment. For example, a

solution with the pH of 6 has 100 times more hydrogen ions than a solution with a pH of 8. The measurement of pH is represented by a balance between hydrogen and hydroxyl ions. A lower pH represents a higher concentration of hydrogen ions relative to hydroxyl ions. A higher pH represents a higher concentration of hydroxyl ions relative to the hydrogen ions [2].

2.3. PH process characteristics

Basically, a pH control system measures the pH of the solution and controls the addition of a neutralizing agent (on demand) to maintain the solution at the pH of neutrality, or within certain acceptable limits. Titration curves provide information about acids and bases in addition to analyzing the quantity that is present [4]. They can provide information about the strength of the acid or base, the number of cognizable groups, ionization and hydrolysis constants, and molecular weight. A titration curve is a graph of pH vs. volume added. Because of the logarithmic nonlinearity, the gain of a pH process to change.

For the strong acid/strong base system, the gain at the equivalence point is extremely high and it occurs at $\text{pH} = 7$, which is neutral pH. Control of this system near pH 7 would place very high demands both on the accuracy of the control system and on the range ability of the reagent delivery system.

pH is only a measure of the concentration of dissociated hydrogen ions present in a solution. When a solution contains a weak acid, most of its hydrogen ions are undissociated. This reasoning can be applied to the weak alkali by considering hydroxide ions (OH^-) instead of hydrogen. These undissociated hydrogen ions dissociate and combine with hydroxide ions when titrated with a base reagent, and there is little effect on the pH solution until all the undissociated hydrogen ions are used. Hence, the solution is buffered against pH changes [5]. Buffering explains the apparent contradiction of a solution containing a weak acid requiring more alkali to change its pH from say 3 to 7 than a solution containing only a strong acid. A strong acid is 100% dissociated and hence has no buffering capacity. Unfortunately, for any realistic chemical system, there is no unique relationship between $[\text{H}^+]$ or pH and the required volume of neutralizing reagent. The reason for this non-unique relationship between pH and effective acidity/alkalinity is chemical buffering, hence the pH is nonlinear in nature [5, 6].

2.4. Significance of pH control

Neutralization is a common practice in wastewater treatment and waste stabilization. If a waste stream is found to be hazardous because of corrosives, neutralization is the primary treatment used. Moreover, neutralization is used as a pre-treatment system before a variety of biological, chemical, and physical treatment processes. Since many chemical treatment processes, such as metal precipitation, coagulation, phosphorus precipitation, and water softening are pH dependent, the pH of these processes is adjusted to achieve maximum process efficiency. Furthermore, the pH of the effluent wastewater from different industrial activities also requires adjustment prior to its discharge into receiving water bodies.

A constant pH value is vital for some production processes in the biotechnology industry. As an example, efficient pH control is needed to maintain a pH value with a small tolerance in order to ensure the optimal performance (e.g. activity and growth) of certain cultures of microbial and animal cells [6,7, 8]. Normally, in animal cell cultures, the optimal pH value for maximum cell growth is, approximately, a pH value of 7.4. In a bioreactor pH control is crucial in order to prevent the micro-organisms from dying as these microbial populations are very sensitive to the environment.

2.5. Brewery Waste Water Treatment Techniques

Basically, wastewater treatment methods can be divided into three categories which are physical, chemical and biological wastewater treatment processes [2]. For almost all combinations of requirements in terms of effluent quality, land availability, construction and running costs, mechanization level and operational simplicity there will be one or more suitable treatment processes. The selections of specific unit processes depend not only on the nature of wastewater, including degradability and treatability by selected processes, but also on discharge requirements [1, 2].

Physical treatment is for removing coarse solids and other large materials, rather than dissolved pollutants. It may be a passive process, such as sedimentation to allow suspended pollutants to settle out or float to the top naturally.

Chemical treatment processes are the processes used for the treatment of wastewater in which change is brought about by means chemical reactions. The principal chemical processes used for wastewater treatment include chemical coagulation, precipitation, disinfection and oxidation, ion

exchange and others. This type of treatment mainly relies on addition of chemicals and is applied when the wastewater cannot be treated biologically [6].

Due to its simplicity and flexibility biological wastewater treatment is the most utilized and the best economical solution for treatment of biodegradable wastewater. Organic components in brewery effluent are generally easily biodegradable as these mainly consist of sugars, soluble starch, ethanol, volatile fatty acids [2.6]. The effluent has a low content of non-biodegradable components. Brewery wastewater normally has a COD: BOD ratio of 1.5 to 1.7 indicating that the wastewater is easily degradable [6].

2.6. PH Neutralization Process

Neutralization is a process for reducing the acidity or alkalinity by mixing acids and bases to produce neutral solution. Acidic or basic wastewater must be neutralized prior to discharge for minimum impact on environment. Neutralization is considered as a preparatory step in the wastewater treatments because many of the subsequent wastewater treatment are pH dependent. The regulations on the quality of industrial waste have become increasingly stringent in recent years. Industrial waste must be neutralized before it is discharged as effluent from manufacturing plant.

A process effluent composed of variety of components has a varying titration curve that defeats effort to attain smooth neutralization on a sound economic basis unless the pH controller can adapt to feedback control conditions ranging between oscillatory and over damped. However, controlling the pH of an effluent stream is often one of the most troubles in some aspects of wastewater system design. The task is so difficult because pH is most unstable at the desired neutral condition.

In wastewater treatment, the pH control system must perform the same task, but with the added problem of working with a flowing stream of ever-changing composition. Proper system design requires detailed information about the flow, pH, and alkalinity or acidity of the wastewater and about how much and how fast these parameters change. A typical pH control system consists of one or more reactors, mixer, measuring elements, controllers and reagent delivery systems.

The neutralization process has long been taken as a representative benchmark problem of nonlinear chemical process control due to its nonlinearity and time-varying nature. Effective modelling of a pH neutralization plant is not a recent issue. However, due to the nonlinear characteristics and complexity of this type of system, research on how to provide a good dynamic model of a pH neutralization process, which was first started in the 1970s or earlier, still continues.

A rigorous and generally applicable method of deriving dynamic equations for pH neutralization in Continuous Stirred Tank Reactors (CSTRs) was presented by McAvoy in the year 1972 [7]. The research work done by McAvoy was essential to the development of the fundamental modelling approach of the pH neutralization process in CSTRs. A model for the pH neutralization process with a single-acid single base system was developed. This model has been widely accepted in the literature for process identification.

The research group of Henson & Seborg is another group that has published work on adaptive nonlinear control applied to a pH neutralization process. That publication is now recognized as an important paper and point of reference in the field of pH control. The group implemented the controller and evaluated its performance on a bench scale pH neutralization system in order to gain additional insight in terms of the practical application [9]. The nonlinear controller was developed by applying an input - output linearization approach to a reaction invariant model of the process. ShahinSalehi, Mohammad Shahrokhi, and Ali Nejati The controller also utilized an open - loop nonlinear state observer and a recursive least squares parameter estimator [10,22].

2.7. Nonlinear PH control

There are many reasons why chemical processes should be effectively and efficiently controlled. During its operation, a chemical plant must satisfy several requirements imposed by its designers and environmental conditions in the presence of ever-changing external influences (disturbances). Among such requirements are the following: safety, production specifications, environmental regulations, operational constraints and economics. Among these requirements is the need for the pH control which encompasses all of these issues. Control of pH is important to many processes including: wastewater neutralization, chemical and biological reaction, production of pharmaceuticals, fermentation, food production, municipal waste digestion, acid pickling/etching processes, coagulation/precipitation processes, boiler water treatment, and cooling water treatment.

Basically, a pH control system measures the pH of the solution and controls the addition of a neutralizing agent (on demand) to maintain the solution at the pH of neutrality, or within certain acceptable limits. These pH control systems are highly varied, and design depends on such factors as flow, acid or base strength or variability of strength, method of adding neutralizing agent, accuracy of control (i.e., limits to which pH must be held), and physical and other requirements.

In general pH control methods can be divided into three main categories. The first category is an open loop type of control scheme in which the control valve opening is kept at certain positions for specific time durations. A specific pH value in the reactor tank is not really the main concern. Normally this type of control approach is used for start - up and shutdown of a process or at an initial or pre- process stage within a multistage neutralization process in which at the later stages of the process involve a feedback controller to control the pH value to a specific value or within a range of values.

The second category is the most popular and commonly used approach and is based on feedback control principles. Unlike the open loop control approach, this type of control scheme involves a direct relationship between the control valve opening and the pH value in the process. The general idea is that when the pH value is higher than the desired value the control valve opening is decreased. Conversely, if it is lower than the set point then the control valve opening is increased. This control approach is also known as a corrective control approach. This is because the control action will take place once there is a discrepancy between the process variable and the required set point. There are many types of feedback control schemes that have been published and discussed by previous researchers. The most widely used type of controller for this feedback control approach is the Proportional, Integral and Derivative (PID) type of controller together with the closely associated variations on this control algorithm involving Proportional control (P) or Proportional plus Integral control (PI).

The third control method that is widely used in this type of application is feedforward control. In this control approach the controller will compensate for any measured disturbance before it affects the process (i.e. the pH value in the case of this application). In order to implement this control approach it will normally be necessary to make more measurements on the process. In the case of a pH process the disturbances could arise from unexpected changes in the concentrations of both solutions as well as changes in the flow rates for the two streams. Thus, with a properly designed feedforward scheme, if a disturbance occurs the controller will react before the pH value in the reactor tank is significantly affected. Based on this principle this feedforward control approach is also known as a form of preventive control. The preventive control approach is very much faster than the corrective control approach. Often, in an ideal case, a controller will involve a combination of corrective control and preventive control. It is unusual to have a controller which involves only feedforward control. This is because the feedback control scheme will handle or react to any unknown or unmeasured disturbances (which are unmanageable by means of feedforward control

alone). At the same time the feedforward control scheme will react faster to any measured disturbance before it affects the process.

2.8. PH Control Techniques

A number of approaches have been proposed in the literature in recent years to solve pH control problems. In both nonlinear and linear control techniques, researches have been proposed and proved on neutralization processes.

2.8.1. Conventional method such as feedback control.

The most widely used simple feedback control strategy applied to pH control involves the PID algorithm. Andrey Popov, Adel Farag and Herbert Werner [11] has proposed Multi-objective Optimization Genetic Algorithm (MOGA) approach for tuning of a PID controller in pH neutralization process. By using a combination of both methods to find a fixed-gain, discrete-time PID controller for a chemical neutralization plant which gives superior efficiency.

Qinghui Wu, Zongze Cui [12] has proposed nonlinear compensator based PI controller for neutralization plant which gives good dynamic and steady-state performance and withstand large disturbances. PID controllers, when used alone, can give poor performance when the PID loop gains must be reduced so that the control system does not overshoot, oscillate or hunt about the control set point value. They also have difficulties in the presence of non-linearity, may trade-off regulation versus response time, do not react to changing process behavior, and have lag in responding to large disturbances.

2.8.2. Intelligent control strategies

Intelligent control strategies try to imitate human way of thinking and decision making using artificial intelligence (AI) based techniques such as fuzzy logic whereas on the other hand adaptive mechanism ensures adjusting of the controller parameters. Such as adaptive control, fuzzy control, multiregional fuzzy control and genetic adaptive control are some of intelligent control systems.

A. Fuzzy Logic Control

Ilanur MuhainiMohd Noor and Muhamad Kamal M [14] Amin The control system of pH level in this project is done by using LABVIEW with the addition of fuzzy logic controller of MATLAB. Block diagram of the whole system is constructed in LABVIEW and the calculation of the amount

of acid and alkali to be added to the process tank to maintain its pH level at neutral is done by fuzzy logic controller Control of pH in mix tank have to take into consideration of flow rate which is controlled by several valves which enable either acid or base to be pumped into mix tank.

Ranganath Muthu and Elamin EI kanzi [15] from University of Bahrain designed fuzzy logic controller (FLC) to carry out simulation of pH neutralization process. It was concluded from the simulation results that the FLC is able to control the pH neutralization process better. Simulation was carried out in MATLAB environment using Simulink and Fuzzy logic tool box.

S. Joe Qin et. al [16] proposed a multi-region fuzzy logic controller for nonlinear process control. PI type of fuzzy controller which uses only control error and change in control error is not capable of detecting the process nonlinearity and makes a control move accordingly. Due to this reason the pH neutralization process is divided into fuzzy regions such as high gain, low gain, large time constant and small time constant Depending on the regional information fuzzy controller were designed, where auxiliary process variable help to detect the process operating region. It was concluded that the resulting multi region fuzzy logic controller gives satisfactory performance in all regions.

ShahinSalehi et.al [17] addressed on adaptive control scheme based on fuzzy logic for pH neutralization process. No composition measurement was required for the implementation of proposed scheme. Stability of the closed loop system was established and it was shown that solution of the closed loop system is uniformly ultimately bounded and under a certain condition, asymptotically stability was achieved. Simulation results indicated that proposed controller had good performance in set point tracking and load rejection and was much better than that of a tuned PI controller.

In 2011 Parekh R Antina and his colleagues published a paper on a new form of advanced Control system for pH neutralization processes [18] involving a technique based on the fuzzy logic approach. In this paper, a rule-based controller that incorporates fuzzy logic controller has been designed and evaluated. Through simulation study, it has been shown that the estimated parameters are in good agreement with the experimental values. Also the proposed fuzzy logic controller has given an excellent tracking and regulation performance compare to that of the velocity form of PI control and the nonlinear adaptive control systems.

ParikshitKishor Singh et.al [19] presented fuzzy logic based control scheme for pH neutralization process .This control scheme uses genetic algorithm to optimize fuzzy inference system. Again adaptive neuro fuzzy inference system for pH neutralization process is developed. Performance of

both control schemes were compared for servo and regulatory operations. It was concluded that the adaptive neuro fuzzy inference system based control uses fewer rules as compared to optimized fuzzy logic based control.

B. Fuzzy PID controller

Conventional PI controllers have been extensively used in industry due to their simplicity in design and tuning for general linear systems. However conventional PI controllers are generally insufficient to control extremely nonlinear pH neutralization processes. To improve upon conventional PI controllers, fuzzy logic is used [20]. Fuzzy logic based PI controllers are more robust than conventional PI controllers because they can cover a much wider range of operating conditions, and can operate with noise and disturbances of different natures. Further, fuzzy logic based PI controllers are customizable, as it is easier to understand and modify their rules, which not only use a human operator's strategy but also are expressed in natural linguistic terms [21].

M.F. Zamil, Y.T. Chow and M.A. Hussain [23] they focus on the segmentation of fuzzy logic to improve nonlinear control for conventional PID controller in pH neutralization system. The conventional controller which integrate with the fuzzy logic approximation is proposed in this paper. In addition, the designed controller will be evaluated for servo and regulator cases. The performance and the analysis will be compared with a conventional PID controller in the same control system setup. As a result, the proposed controller show superior performance in all analyzed cases and able to overcome nonlinear effect in pH neutralization application.

C. Model predictive control

The same approach presented in the earlier pub listed work Jonas B. Waller and Hannu T. Toivonen [24] was used in modelling and in controller design for the pH - reactor where the composition of the incoming waste- the issue of controlling nonlinear processes by the use of the nonlinear model predictive control formulation. To handle the nonlinearities, a neuro-fuzzy process model is suggested as a means to model processes with strong nonlinearities depending on the operating region. In this paper the neuro-fuzzy approach is used for the modelling and control of a strongly nonlinear pH neutralization process, both in the face of set-point changes and in the face of un modelled disturbances

Wan, F., Shang, H., Wang, L.X. [25] presented modified model for the neutralization process of Stirred Tank Reactors (CSTR) reactor. Also investigates the effect of important reactor parameters such as ionic concentrations and acid and base flowrates on the dynamic behavior .N. R. Lakshmi Narayanan, P. R. Krishnaswamy and G. P. Rangaiah [26] has formulated the adaptive internal

model control (AIMC) strategy by combining the concepts of adaptation as in robust non-linear control law (RNCL), non-linear internal model control (NIMC) structure and strong acid equivalent (SAE). The resulting control system provides significant improvement in disturbance rejection compared to the performances of RNCL and SAE-based NIMC when used alone in pH neutralization. PH controllers using robust nonlinear control optimize the desired closed loop speed of response while satisfying robust stability or disturbance suppression constraints.

Model predictive control (MPC) is one of the most successful controllers in process industries algorithms that control the future behavior of a plant through the use of an explicit process model [27]. Therefore, the core of the MPC algorithm is a dynamic model. MPC based on linear models are acceptable when the process operates at a single set point and the primary use of the controller is the rejection of disturbances but many chemical processes, however, do not operate at a single set point, and they are often required to operate at different set points depending on the grade of the product to be produced. Because these processes make transitions over the nonlinearity of the system, linear MPC often results in poor control performance.

D. Artificial neural network ANNs

The impetus for employing artificial neural network ANNs to control nonlinear systems is due to their advantages over other nonlinear modeling paradigms. PH process can have characteristics, including nonlinearity, which render it difficult to control. Consequently, a great deal of research effort has been applied to pH control and numerous different control strategies have been proposed. Several workers have applied model-based control, employing empirical models, to pH control. Nah et al. [28] applied a neural network based internal model controller to a simulated CSTR pH neutralization process. The nonlinear control system includes dead time compensation in terms of a Smith predictor. Pottmann and Seborg [29] applied a neural network model predictive control algorithm to a pH neutralization process. Draeger et al [30] applied ANN based Dynamic Matrix Control to a neutralization reactor. These research studies have confirmed the feasibility of applying nonlinear model based control to pH control, and furthermore, some of these studies have demonstrated an improvement in control performance over conventional linear control. Hence there is considerable motivation for investigating ANN based control of the inline pH process which has characteristics that render it difficult to control. The following section reviews the main types of ANN based control structures and begins with the problem of identifying inverse process models which some ANN control strategies use.

This approach remains one of the most popular and commonly used methods in the development of fuzzy logic controllers. In this research the Mamdani type of approach has been used to develop a fuzzy logic controller for the pH neutralization plant. Although all these techniques have been proved successfully on real plants, the main difficulty is still the necessity of developing a model that adequately represents the pH process in any operating condition. To solve this problem, this paper discusses a technique based on fuzzy control to design pH controllers without the necessity of any plant model.

Form the above review it is clear that different literatures are reviewed about different PH neutralization process, brewery waste water treatment techniques, and PH neutralization control mechanisms. In this thesis PID and fuzzy controller for PH neutralization waste water treatment process is modeled and simulated.

3. THE PH NEUTRALIZATION MODEL OF THE CASE STUDY PLANT

3.1 Kilinto wastewater plant

A flow diagram of a typical WWTP process is shown in Figure 3.1. The collected wastewater enters the plant and passes through bar screens. The large items such as rags, sticks are screened and are disposed later.

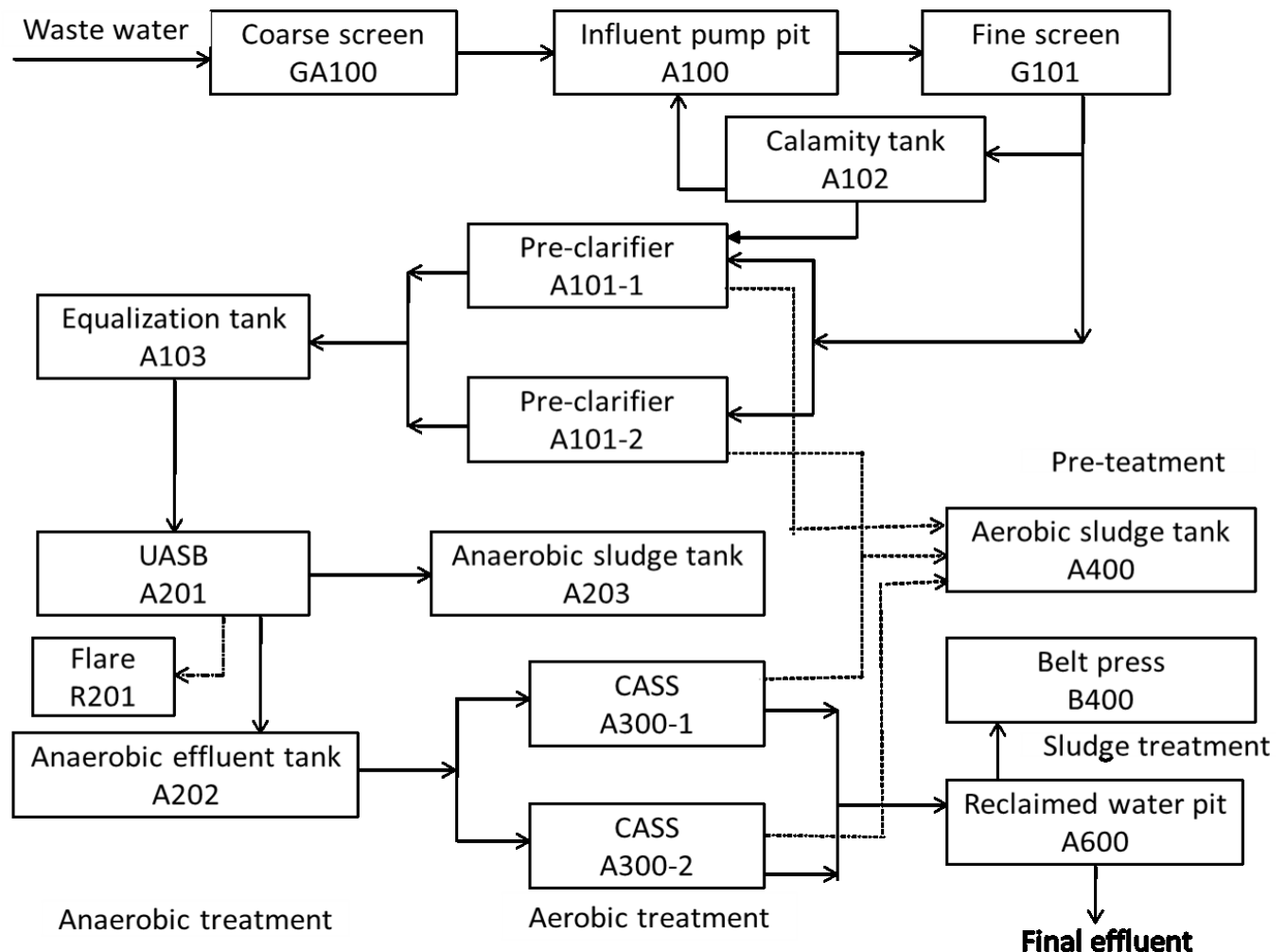


Figure 3. 1: process flow chart [2]

Influent pump pit (A100) function used for wastewater collecting and then the wastewater will be pumped to process unit by pumps. Pneumatic valves A100 and G101 determine wastewater in influent pump pit pumped to calamity tank or pre-clarifiers, removal of suspended solids in

wastewater, to prevent inorganic matters like sand, coal ash, diatomite etc. accumulation in UASB reactor.

When pH meter value in influent pump pit is higher than 10.0 or lower than 10.0, or inline COD analyzer value is higher than 4,000 mg/l, A100 open and G101 close, wastewater will be pumped to calamity tank automatically holding tank for temporarily storing high COD concentration (COD > 4000 mg/l) wastewater or severely high pH (pH > 10.0) or severely low pH (pH < 5.5) wastewater, also can be used as a holding tank for temporarily storing normal wastewater being out of specification.

Of course, all these limits can be set in computer. Then pH value controlled between 6.0 and 9. Equalization tank water retention time should be controlled between 6 and 10 hours, to make sure partial pre-acidification. UASB (Up-flow anaerobic sludge blanket) uses an anaerobic process whilst forming a blanket of granular sludge which suspends in the tank. Wastewater flows upwards through the blanket and is processed (degraded) by the anaerobic microorganisms.

Then the wastewater is delivered to aeration (Anaerobic system process AND/OR Aerobic system process) tanks by intermediate pumps. Process air is provided by single-stage, centrifugal blowers to and around the aeration tanks. During normal operation partial of the sludge from the secondary clarifiers, called returned activated sludge (RSL), enters into aeration tanks through sludge pumps. When the RSL and the wastewater are mixed together, microorganisms in activated sludge use the Oxygen provided by the fine bubble diffusers located on the bottom of the aeration basins to break down the organic matters. The remaining sludge from the secondary clarifiers and the sludge from the primary clarifiers are pumped to the anaerobic digesters to produce biogas. The liquid from the secondary clarifiers flows to the chlorine contact tanks where chlorine is injected into the flow to kill most bacteria, and then the final effluent is discharged to the river. During the whole process, physical, chemical and biological sub-processed involved. The process is highly nonlinear and dynamics.

3.2 Kilinto Brewery industry amount of wastewater

Kilinto Brewery industry consumption of water ranging from 4 to 11 hl water/hl beer. The Water consumption in the industry is divided into 2/3 used in the process and 1/3 in the cleaning operations.

Kilinto Brewery industry has two phases of productions. The Wastewater Generation Use Areas are the following lines.

- Packaging
- Utilities
- Cellars
- Brew house

The amount of wastewater production of each phase are

- Maximum technical beer production: increasing to finally 1.5 Mhl/y (projected in 2018). Phase 2 foreseen for 3.0 Mhl/y
- Water consumption 5.0 hl water / hl produced beer; Production 300 d/y, 24h/d.
- A maximum wastewater discharge of 3.8 hl wastewater/hl beer.
- Maximal wastewater quantity for phase 1 (2018): 1,900 m³/day (80m³/h, based on 7,200 h/yr).
- But project sales for the first year is 600,000 hl, so less waste water in the first years.
- Peak flow phase 1 (Before equalization tank): 120 m³/h

3.3 pH neutralization

This section describes the pH neutralization system development of the plant in detail. There are three tanks involve in the process to maintain the neutral value. One is the acid tank and the other is alkali or base tank and neutralization tank. Based on the value of pH sensed by the pH sensor in the neutralization tank, either one of the tank which consist of acid or alkali will be pumped into the neutralization tank. If the pH sensor in the neutralization tank shows pH less than 7 then it is considered as acidic. Therefore, certain amount of alkali will be pumped into the neutralization tank to maintain the pH to neutral value. On the other hand, if the pH sensor in the neutralization tank shows pH more than 7 then it is considered as base. Therefore, certain amount of acid will be pumped into the neutralization tank to maintain the pH to neural value. If the pH sensed by sensor

in the neutralization tank shows the pH almost 7, then both valve for alkali and acid will be closed to make sure that none of it is pump into the neutralization tank.

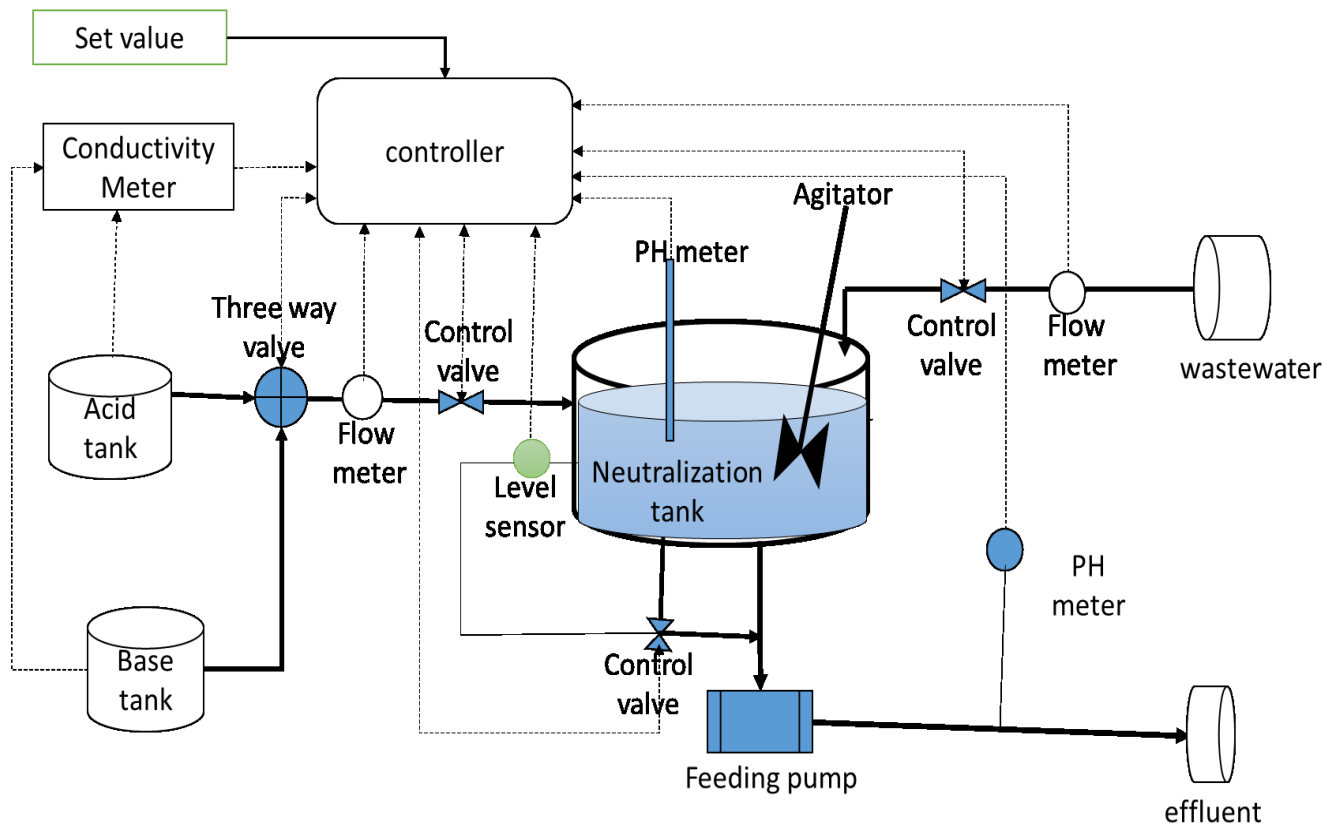


Figure 3.2: The pH neutralization block diagram of plant model

As shown in the block diagram, there are two flow transmitters that indicate the flow rate for the acid or alkaline and wastewater streams. The flowrate for both streams can be controlled individually by using the control valves which are the acid or base stream control valve and the wastewater stream control valve. Three way valve is used to select acid or base based on the behavior of wastewater available in the neutralization tank. There is also a motorized agitator in the reactor that is used to mix the solution. A pH sensor measures the pH value of the solution in the neutralization tank. The conductivity meters in the acid and alkaline tanks are used to monitor the concentrations of the solutions. There is another section which is included in this diagram. This is the discharging section which starts from the outlet of the neutralization tank (i.e. The product of the neutralization process) and ends at the discharged tank. The solution in the discharged tank will be treated before being released into the environment.

In general the design of this plant involves control of the pH value of the solution in the reactor to a desired level by controlling the feed flow of the alkaline stream.

3.3 Overall System Architecture

The control action of the kilinto brewery wastewater treatment pH neutralization design is shown in figure 3.2. The overall system architecture of the plant has three different functional levels as shown in the figure. The first level is known as the Plant and Field Instrument Layer, the second level is the Data Acquisition System Layer and the third level (shown at the top) is the Supervisory Computer System Layer.

The first level (the Plant and Field Instrument Layer) involves the physical plant itself and consists of the primary elements such as the pH meters, conductivity meters and flow transmitters that provide information about the relevant process variables to the system. This level also has some final elements such as the control valve, pumps and agitator. In addition, this level will also provide some status input information to the upper levels (e.g. ON/OFF switch status input).

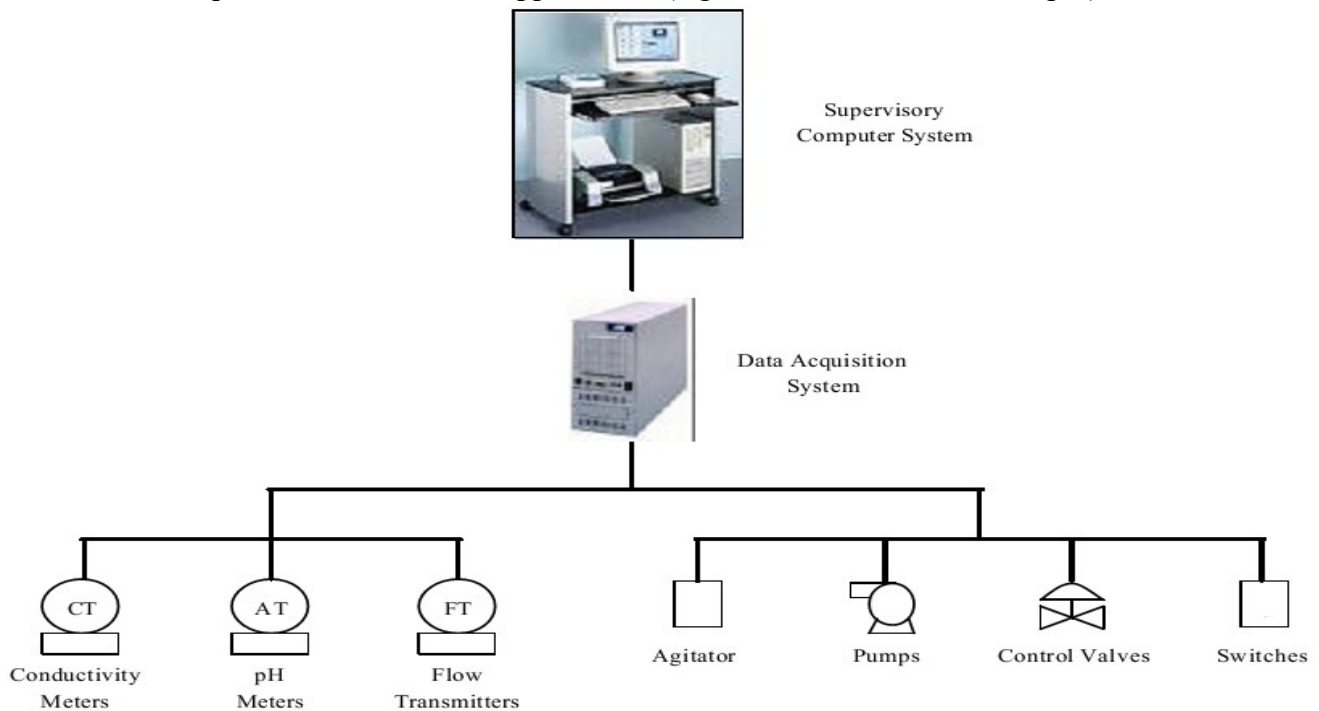


Figure 3.3: Overall system architecture of the plant showing the three functional levels

The main function of the second level is to establish communication between the first layer and the third layer as well as data retrieval and processing functions. The main function of the data acquisition is to process all measured data and transfer them between the computer and the process actuators back and forth. The second and the third levels are normally very closely interconnected and can be considered as one system although they involve more than one processor. Such a system may be termed a Distributed Control System (DCS). The computer system in the third layer should

be compatible and comply with all protocols used in the data acquisition system. The third layer provides a platform for monitoring and controlling the whole operation of the plant.

3.4 The neutralization Tank

The reactor tank is very crucial in this research as this is where the neutralization reaction process takes place and where the output measurements are taken. Figure 3.3 shows the simplified diagram of the physical arrangement of the reactor tank.

The outlet point is positioned to provide a maximum storage volume for the tank. The minimum operating volume is needed, as the agitator will not be able to mix the solution properly if the volume is smaller than this value. Thus most of the simulation results are based on a volume of mixing solution of approximate minimum and maximum volume. The main purpose of this agitator is to mix both solutions completely and homogeneously. In addition to that, it will also accelerate the neutralization reaction process. The agitator produces some turbulence in the tank in order to mix the solution satisfactorily. The pH value from the online pH meter is also relatively consistent, indicating that the agitator works adequately and its turbulence does not adversely affect the measured signals. And also the pH meter provides the main feedback of the process variable to the controller whereas the flow meters and conductivity meters can be used to provide inputs that indicate whether or not the system can be controlled.

3.5 Instrumentation and Measurements Involved

There are six main process variables that will determine the behavior of the pH neutralization process for this plant. As given in the table below (i.e. Table 3.1), the instrumentation that provides the main required process variables from the plant involves one pH meter, two flow meters and two conductivity meters and level sensor.

Table 3.1: List of process variables

No	Process Variable	Instrument
1	pH value from the reactor tank	pH Meter
2	Concentration in acid tank	Conductivity Meter
3	Concentration in alkaline tank	Conductivity Meter
4	Flowrate for acid stream	Flow meter

5	Flowrate for alkaline stream	Flowmeter
6	Level sensor	Meter

3.5.1 PH Meters

The pH meter provides the main feedback of the process variable to the controller whereas the flowmeters and conductivity meters can be used to provide inputs that indicate whether or not the system can be controlled. Therefore the accuracy and reliability of these instruments are also important in order to ensure that the performance of the controller is satisfactory and consistent. PH meter also known as pH sensor. PH sensors measure hydrogen ion activity and produce a voltage. The sensor operates based on the principle that an electric potential develops when two liquids of different pH levels come into contact on opposite sides of a thin glass membrane. This was discovered by Max Cremer in 1906 [31]. The pH sensors today are composed of two main parts; a glass electrode known as the measurement electrode and the reference electrode. The tip of the measurement electrode is a thin glass membrane. The thin glass membrane is able to facilitate ion exchange. As the ions exchange they create a voltage that is measured by the measurement electrode. This voltage is converted into a corresponding pH level. The reference electrode's potential is kept constant. This is possible because the reference electrode's fill solution is kept at a pH of 7 [31]. PH sensors are used in wastewater treatment plant mainly to monitor plant conditions, track biological treatment process conditions, and control acid base additions for pH adjustments. The pH values for different wastewater treatment processes are different.

3.5.2 Conductivity Meters

The meter has two parts: the process electrode and the controller. The main function in each case is similar to the functions within the pH meter. The process electrode measures the density of ions in the aqueous solution in the form of an electrical current. Normally the range of the generated electrical current is very small. The controller displays the measured current using suitable basic units of measurement, which are milli Siemens/cm (MS/cm) and micro Siemens/cm ($\mu\text{S/cm}$). The conductivity value relates to the concentration value of an aqueous solution and a different solution will involve a different relationship. A few sets of laboratory experiments had been carried in order to find a suitable or appropriate range for concentrations for the plant. The main factor was to be able to achieve a linear relationship between the conductivity and the concentration of the solution.

3.5.3 Flow meters

Flow meters measure the flow rate of concentrations of wastewater in general. Some of the most widely used flow meters includes: magnetic flow meters, ultrasonic, flumes and weirs, differential-pressure, mechanical and mass-flow meters. These flowmeters or flow transmitters will provide flowrate indications for the acid stream and for the alkaline stream. A magnetic flowmeter is suitable for wastewater or other dirty fluid applications as there is no direct contact between the fluids being measured and the measuring parts or elements. The operating principle of a magnetic flowmeter is based on Faraday's law of electromagnetic induction. The fluid acts as a conductor and the induced potential is proportional to the average flow velocity which is perpendicular to the flux lines. The magnetic flowmeter can also be considered as divided in two parts. The first part is a sensor in which the magnetic field is normally mounted along the pipeline. The second part is the transducer. This is where all the conversions of the measured variable into a desired form in terms of the electrical signal take place.

Flow meter is used in different types of applications to measure the volumetric flowrate or mass flowrate. The specific application defines the type and capacity of the flow meter. Fluids, gases and liquids, are measured in terms of volumetric flowrate and mass flowrate. Both are related to ρ material's density with volumetric flowrate denote $F_a + F_b$ by and mass flowrate by dM/dt in the equation.

$$dM/dt = (F_a + F_b) \rho \quad (3.1)$$

3.5.4 Control Valves

In a process control application, control valves represent an important form of final element that will determine the performance of a controller. In general there are three types of control valve characteristics, which determine the relationship between the control valve opening and the actual stream flowrate. The first type of control valve characteristic is termed linear opening, the second type is called quick opening and the third type is called an equal percentage type of valve.

The linear opening type, this form of control valve is generally required for applications in which the differential pressure drop across the control valve is relatively constant over the valve travel range. This type of situation commonly arises for control of liquid level and flow.

The quick opening characteristic valve exhibits a rapid increase in flowrate as the valve opens even with a small change of opening. The movement of this type of valve can be extremely small relative

to small changes in the controller output thus the valve has an inherently high range of operability. The typical application for this type of control valve is a frequent on-off service and this type of characteristic is also useful for processes where immediate large flowrate is required.

The third type of control valve is the equal percentage characteristic valve. The trim for this type of control valve has been designed so that each increment in the control valve opening will lead to an increase of the flowrate by a certain percentage of the previous flow. In general, the response for the equal percentage type of control valve is much slower or less sensitive compared to the fast opening type. This type of control valve is normally being used in processes where large changes in the pressure drop are expected. The type of control valve is also common in temperature and pressure control applications.

3.5.5 Level sensor

The valve is opened and closed according to controlling action according to the added desirable solution. Float switches are one of the most cost effective but also well proven technologies for liquid level sensing. A float switch includes a magnet within a float and a magnetic reed switch contained within a secure housing. The float moves with the change in liquid and will cause the reed switch to either open or close depending on if it's in air or liquid. Although simple in design, this technology offers long-term reliability at an attractive price point.

It is clear that the relationship is linear. The level h in the CSTR is modeled through a mass balance: Differential equation for the height of liquid in the neutralization tank, h , is given by

$$\frac{dV}{dt} = A\rho \frac{dh}{dt} = \rho_a F_a + \rho_b F_b - \rho(F_a + F_b) \quad (3.2)$$

Where, V is the volume of liquid in the tank

ρ is fluid density has value 1000kg/m^3

A is the cross-sectional area of the tank= 1000m^2

F_a is acid flow rate

F_b is base flow rate

The equation describes the height of liquid, has a function of time, due to the difference between flow rates into and out of the tank.

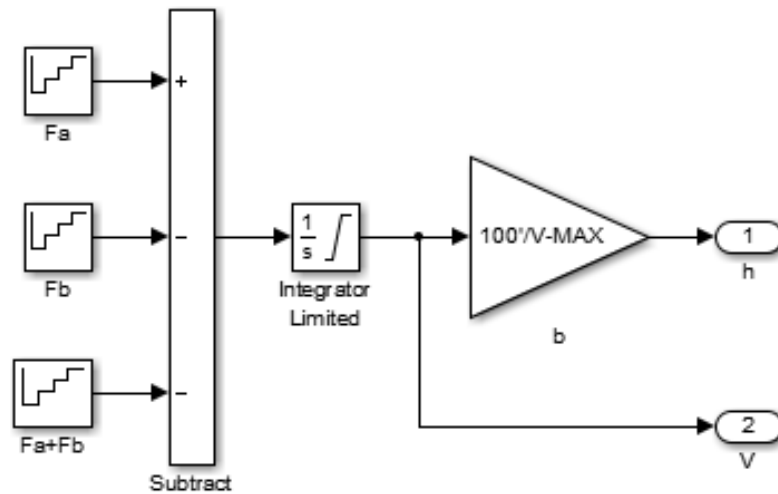


Figure 3. 4 Model of the level in the CSTR

3.6 Overview of the pH Neutralization Process Modelling

A rigorous and generally applicable method of deriving dynamic equations for pH neutralization in Continuous Stirred Tank Reactors (CSTRs) was presented by McAvoy in the year 1972 [26]. The research work done by McAvoy was essential to the development of the fundamental modelling approach of the pH neutralization process in CSTRs. However those early studies concentrated largely on the dynamic behavior of the pH electrode system. Subsequently, two crucial points in developing a pH neutralization process model which describes the nonlinearity of the neutralization process have emerged from published research. The two points are as follows: -

- ⇒ Material balances in terms of hydrogen ion or hydroxyl ion concentrations would be extremely difficult to write down. This is due to the fact that the dissociation of water and resultant slight change in water concentration would have to be accounted for.
- ⇒ Instead, material balances are performed on all other atomic species and all additional equilibrium relationships are used. The electro neutrality principle is used to simplify the equations.

All the procedures outlined in the publications mentioned above have involved the making of assumptions to reduce model complexity. Without such assumptions models can present computational difficulties and can involve major problems in terms of validation and tuning. As

suggested in previous studies, the assumptions underlying the modelling of the pH neutralization process are as follows:-

- i. The acid and alkaline solutions in the reactor tank are perfectly mixed at all times and a lumped parameter compartmental form of model can be used.
- ii. The acid- base reaction process in the reactor tank is instantaneous and isothermal.
- iii. The dissociation of acid and base reaction is complete and the attainment of equilibrium is fast.
- iv. No other reactions occur in the reactor tank.
- v. The time constants for the control valves and measuring instruments are negligible compared to those of the process.
- vi. The volume of the solution in the tank is constant.

3.7 PH models methods

PH models are crudely divided into static and dynamic models and similarly the modelling methods are divided into theoretical and experimental. The borders of these divisions are vague at the best and many models combine static and dynamic model structures (Wiener models) and use both theoretical and experimental methods. The design of the neutralization process depends mostly on factors like:

- ✓ Reaction tank size, which can effect on the neutralization performance (e.g. a large vessel is required when low solubility reagents are present such as calcium lime). The retention time should be minimized.
- ✓ Mixing and agitation for complete elimination of the area of unreacted reagent. The result of insufficient mixing is excessive cycling and poor pH control.
- ✓ The relative location of the vessel inlet, outlet, and measurement probe location for maximum speed of response.
- ✓ Reagent delivery system and reagent addition point location for close pH control.

3.7.1 Static modelling

Static models are valid when the system has reached the equilibrium. The acid-base unit reactions can be considered instantaneous and therefore static modelling is a very natural approach. Static models include titration curves and distribution diagrams. Experimental static models are often

basic tools for product quality control as well as process state indicators. Experimental methods have been used for both qualitative and quantitative analysis.

3.7.2 Dynamic pH process modelling

Dynamic modelling is fundamentally more difficult than static modelling. Static modelling concentrates only on the equilibrium state where the system does not change as a function of time. In the dynamic modelling procedure the behavior of pH and related phenomena are considered as functions of time; they change autonomously even though the changes in the input have already passed.

The dynamic pH-systems can be divided into two categories; the systems where chemical phenomena are significantly faster than flow and mixing phenomena and the systems where this is not the case. These categories are treated in more detail in the following sections.

The characterization involved gathering pH and flow information. Some data was gathered from historical facility records (PH circular charts and flow totalizer readings) however, the existing data did not sufficiently characterize the wastewater.

3.7.3 Preliminary Development of the Mathematical Model

In this study, the semi batch m process model Figure 3.4, consists of a mixing tank with an initial amount of acidic solution (wastewater) and of two input streams of strong acidic (wastewater) and strong basic (reagent) solutions. The aim of this process is to simultaneously neutralize the wastewater already in the mixing tank and the wastewater from the input stream by regulating the flowrate of the reagent solution F_b until the mixed solution stabilizes at pH 7.

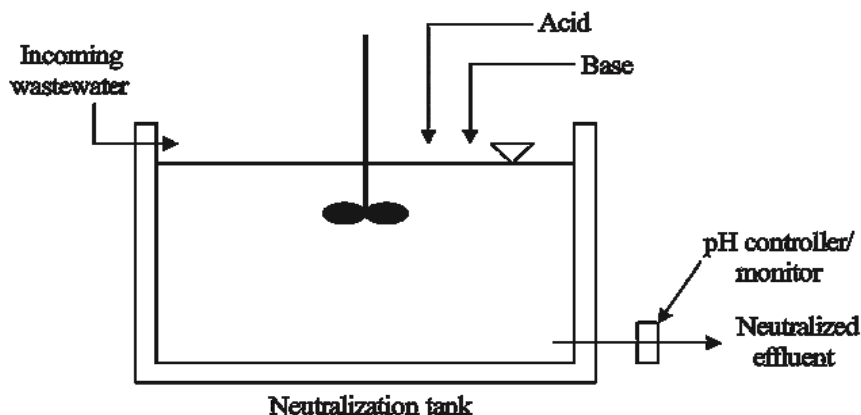


Figure 3.5: Schematic of pH Process in CSTR [7]

The pH neutralization process considered in this thesis is assumed to take place in a Continuous Stirred Tank Reactor (CSTR) with perfect mixing and constant volume, as shown in Fig 3.5. The

CSTR has two influent streams: the hydrochloric acid as the process stream and the sodium hydroxide as the titration stream, and one outlet stream: the effluent stream (ideally neutral solution). The formulation of process dynamic model is based on the principle of material balances, water equilibrium relationship and the fact that the solution must be electrically neutral [23]. The general equation for the conservation of material for the pH process may be written as follows:

$$\begin{aligned} & \text{(rate of accumulation of non reactant species within element volume)} \\ & = \text{(rate of flow of non reactant species into element volume)} \\ & - \text{(rate of flow of non reactant species out of element volume)} \end{aligned}$$

Based on this general equation, two equations have been derived to express the pH process in the CSTR system.

$$V \frac{d}{dt} \alpha = F_a C_a - (F_a + F_b) \alpha \quad (3.3)$$

$$V \frac{d}{dt} \beta = F_b C_b - (F_a + F_b) \beta \quad (3.4)$$

The rate of volume change

$$\frac{dV}{dt} = (F_a + F_b) \quad (3.5)$$

Where, C_a represents the concentration of the acid inlet stream

C_b Represents the concentration of base used in the neutralization

α Represents the concentration of acid ion

β Represents the concentration of base ion used in the neutralization

F_a Denotes the flow rate of acid inlet stream

F_b Represents the flow rate of base used in the neutralization and

V is the volume of the equilibrium tank.

The second part represents a static function. It can be found by writing material balances on Na^+ , β and total acetate ($\text{HAC} + \text{AC}^-$) α and assuming that acid-base equilibrium and electro neutrality relationships hold on.

HAC equilibrium:

Acids are defined as acids that partially dissociate in an aqueous solution and form a chemical equilibrium with an acid dissociation constant K_a .

$$\frac{[AC^-]}{[HAC]}[H^+] = K_a, K_a = 1.8 * 10^{-5} \quad (3.6)$$

Water equilibrium:

$$[H^+][OH^-] = K_w = 10^{-14} \quad (3.7)$$

The water product K_w shows the relationship between hydroxide ions and hydrogen ions in a solution. The potential of hydrogen (pH) is the negative logarithm at base 10 of the hydrogen ion concentration in the solution

The next step is to identify and derive the electro neutrality condition of the non-reactant components. Based on the principle of electro neutrality all solutions are electrically neutral. There is no solution containing a detectable excess of positive or negative charge because the sum of positive charges equals the sum of negative charges.

Electro neutrality:

The next step is to identify and derive the electro neutrality condition of the no reactant components. Based on the principle of electro neutrality all solutions are electrically neutral. There is no solution containing a detectable excess of positive or negative charge because the sum of positive charges equals the sum of negative charges. In the neutralization reaction, there are spectator ions such as $[HAC]$, $[AC^-]$ and $[N_a^+]$. The amount of these spectator ions is dependent on the amount of sodium hydroxide and acetic acid that is present in the solution. The sum of the acetate ion and un-dissociated acetic acid can be combined to give a constant alpha.

$$\alpha = [HAC] + [AC^-] \quad (3.8)$$

$$\beta = [N_a^+] \quad (3.9)$$

Rearranging equation (3.3) and (3.5) gives

$$\alpha = \frac{K_a + [H^+]}{K_a} [AC^-] \quad (3.10)$$

$$[N_a^+] + [H^+] = [OH^-] + [AC^-] \quad (3.11)$$

Where K_a and K_w are the dissociation constants of the acetic acid and water.

After inserting the equations (3.6) and (3.10) into (3.11), we have finally the titration function given by the equation (3.12), which gives the static relationship between α , β and the pH

$$[H^+]^3 + (K_a + \beta)[H^+]^2 + (\beta K_a - K_w - \alpha K_a)[H^+] - K_a K_w = 0 \quad (3.12)$$

Spectator ions, represented by α and β , undergo a simple dilution reaction during neutralization, which makes the calculation of hydrogen ions relatively easy given the concentration of sodium hydroxide, acetic acid and physical constants K_w and K_a .

The pH is given by the equation (3.13):

$$pH = -\log_{10}[H^+] \tag{3.13}$$

The $pH = -\log_{10}[H^+]$ determined using the equation 3.13 for α and β given, than relation can find the pH value ($pH = -\log([H^+])$). The difficulty to solve static equation (3.12) is caused the variable of $[H^+]$ is polynomial in order 3. Much software in recent today can helpful to determine this root, for example Mat lab. The pH values can be found directly after the $[H^+]$ is achieved.

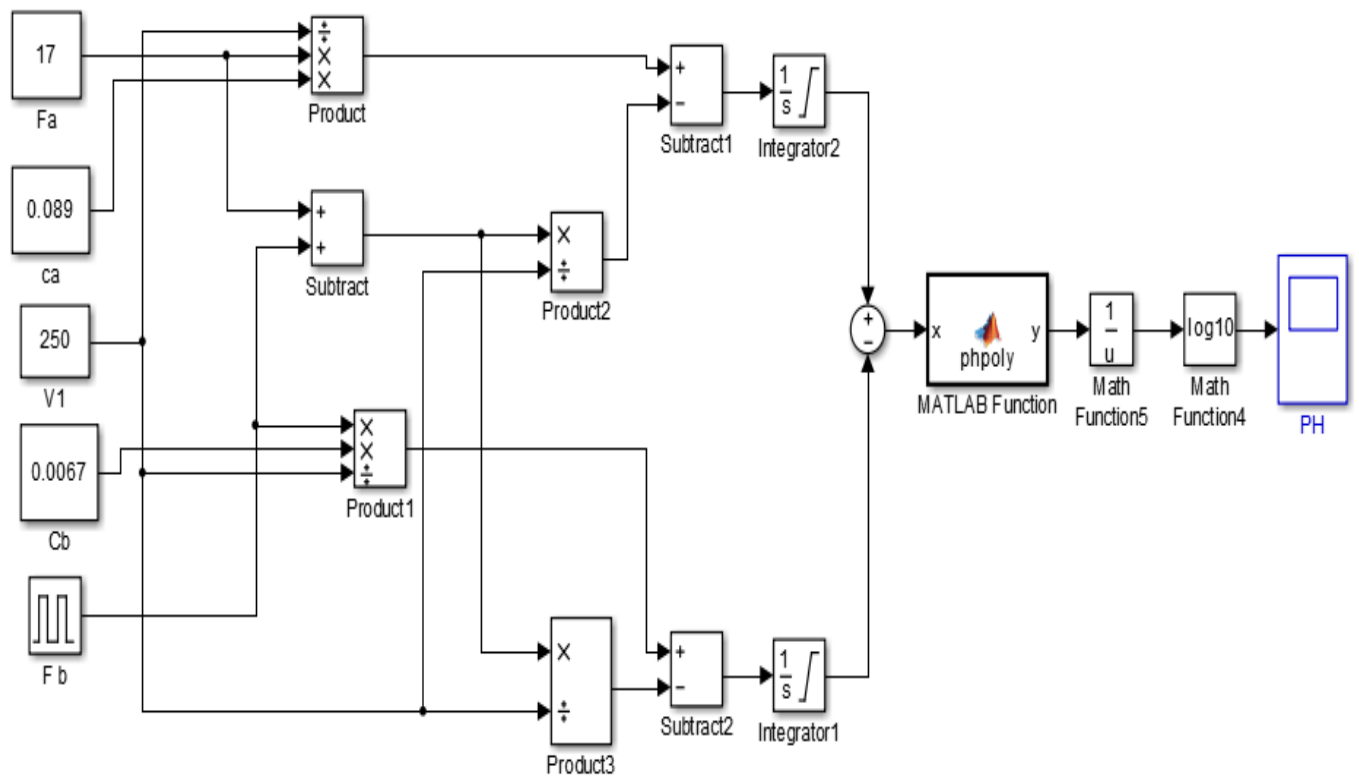


Figure 3.5: plant Simulink model

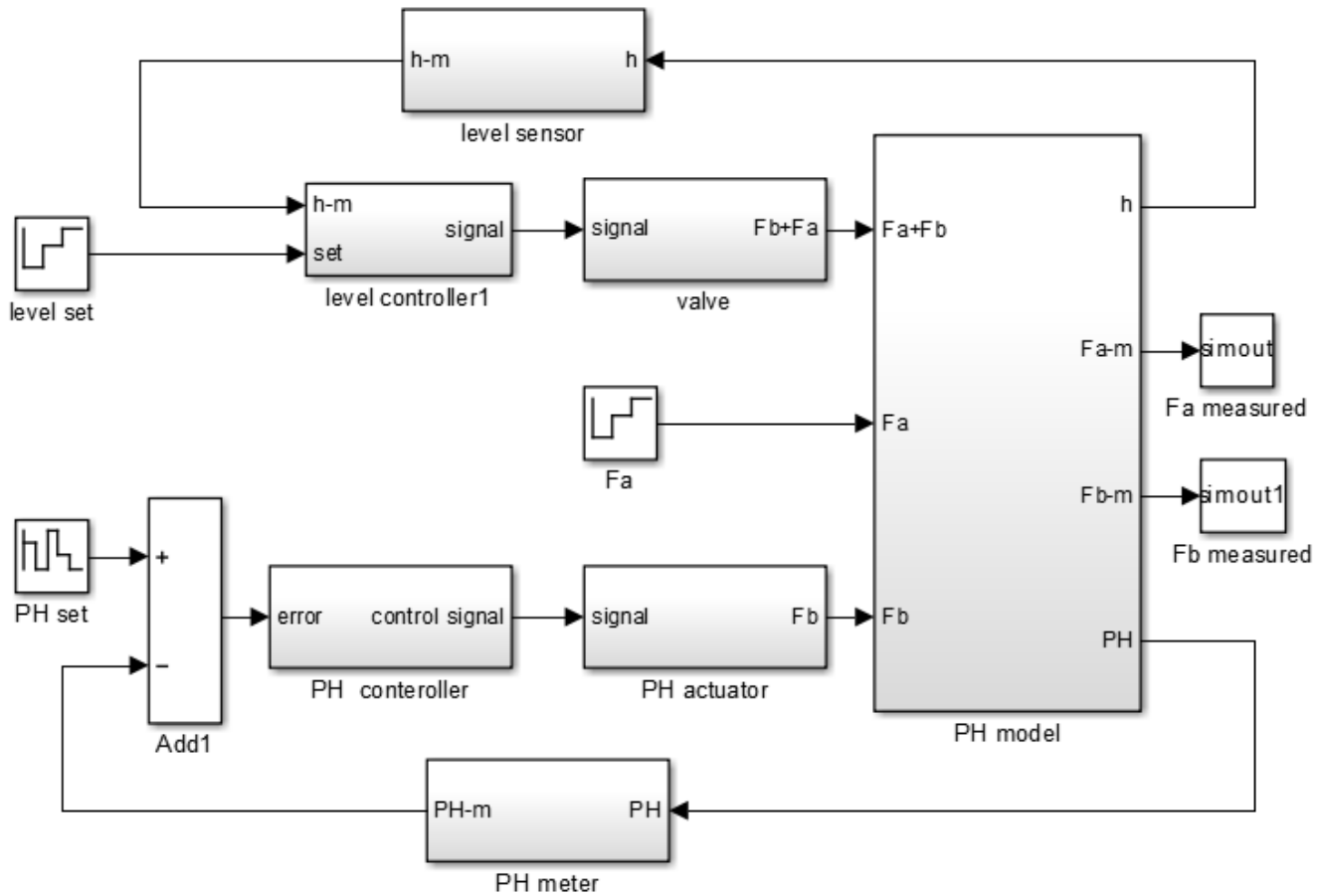


Figure 3.6: MATLAB/Simulink blocks of the pH neutralization on process model

Equation (3.12) is the Physio-chemical pH neutralization equation for the mixer tank. The block diagram of the resulting plant is shown in the Fig. 3.6. Generally, there are three main parts that influence the behavior of this physically based model of a pH neutralization process and these relate to the above equations.

4. CONTROL STRATEGIES

In this section, the application of conventional PID and Fuzzy control to the pH neutralization process is described and discussed as well as the implementation of the PID control in place of the controller. The Fuzzy logic controller is also described and employed to improve the pH response.

4.1. Conventional Feedback Control

The set point and measured pH are compared by the controller to give a pH error pressure signal, which is fed to the control valve on the reagent circuit. Operation of the valve allows reagent to be introduced to the influent reducing the error. This form of control is called feedback control.

4.1.1. Overview of the PID Controller

A proportional integral derivative controller (PID controller) is a control loop feedback mechanism (controller) widely used in industrial control systems. A PID controller calculates an error value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process through use of a manipulated variable [10]. The PID controller algorithm involves three separate constant parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted P, I and D. Simply put, these values can be interpreted in terms of time: P depends on the present error, I on the accumulation of past errors, and D is a prediction of future errors, based on current rate of change.

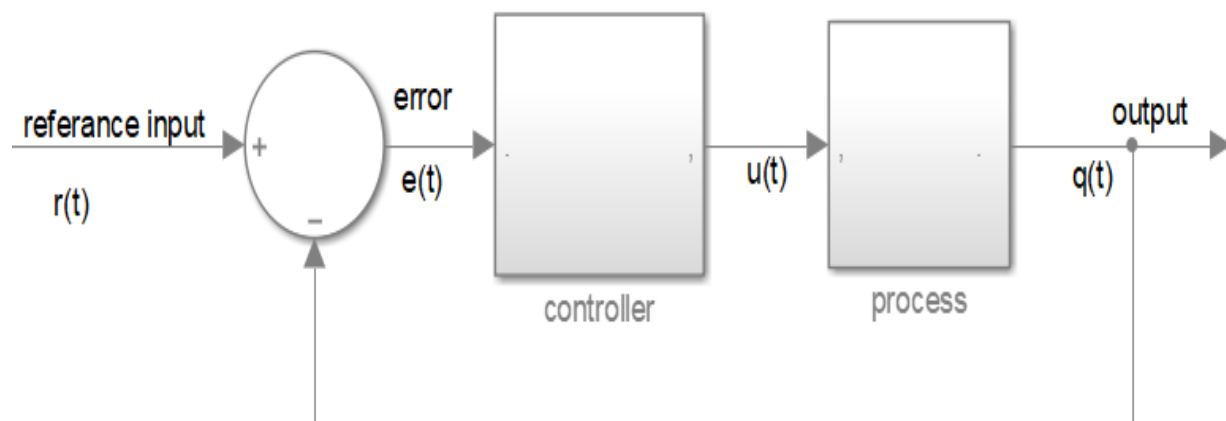


Figure 4.1 : A closed loop PID Controller

The proportional term is a simple gain factor and provides a means of influencing the rate of adjustment of the manipulated variable. For most process applications the proportional control

action has a very straightforward effect on the performance of the controller, especially in terms of the influence of this term on the overshoot and rise time of the output response to a step change of reference. This control action is capable of reducing the offset error but it does not provide a zero offset in typical process applications involving a Type 0 plant transfer function.

The second term in the PID controller is the integral action term. The main advantage of this control action is its influence on the final steady state error value, although it adjusts the manipulated variable in a slower manner than pure proportional action and the integral action can have a destabilizing effect in terms of the dynamic response of the closed-loop system. Integral action is capable of bringing the steady state output value to the desired set point with zero offset for a plant that shows linear behavior and may be described by a Type 0 transfer function.

The final control term is the derivative term. This control action will have no direct influence to the final steady state value of error. However, properly tuned, it can provide rapid correction based on the rate of change of the controlled variable. In many situations the derivative term is omitted because it tends to increase the effect of measurement noise and can thus degrade the overall performance of the controller. In cases where there is no derivative term the PID controller is reduced to a PI controller having only the proportional and integral terms and thus has only two principal parameters for adjustment. For PID and PI controllers inappropriate tuning of the adjustable parameters can result in instabilities within the controlled process.

The controller may have different structures. Different design methodologies are there for designing the controller in order to achieve desired performance level. But the most popular among them is Proportional-Integral-derivative (PID) type controller. Equation (4.1) describes the most basic form of continuous PID algorithm in the time domain. As shown in the equation, the PID algorithm is actually a simple single equation with three control terms; proportional gain, (K_P), integral gain, (K_I) and derivative gain, (K_D). The variable $mv(t)$ represents the controller output while the variable $e(t)$ is the error, which is the difference between the system output (the measured pH in this case) and the set point.

$$M * V(t) = K_P e(t) + K_I \int_0^t e(t) dt + K_D \frac{de(t)}{dt} \quad (4.1)$$

In the simplest forms of PID controller the three adjustable control parameters that influence the control performance and, in most cases, PID control algorithms are able to provide a reasonably

good performance when the adjustable control parameters have been properly tuned. Tuning is adjustment of control parameters to the optimum values for the desired control response. Stability is a basic requirement. However, the control performance also depends on the nature of the process. Different systems have different behavior, different applications have different requirements, and requirements may conflict with one another. The most widely used simple feedback control strategy applied to pH control involves the PID algorithm.

4.1.2. Design of conventional PID controller

To understand the dynamic characteristics of the pH process, i.e., static gain and time constant and to design the PID controller, closed-loop tests are carried out. This classical approach is probably the best known method for tuning PID controllers. The continuous cycling method has also been referred as ultimate gain method. It is trial and error procedure, which can be summarized as follows:

Step1: Firstly the Proportional gain must be set to a minimum value and the other parameters (i.e. Integral and Derivative terms) should be set to give zero action.

Step2: Increase the controller gain by small increments until sustained oscillation occurs after a small set point change.

Step3: The gain should then be adjusted so that the oscillations are maintained with constant amplitude. The value of gain that is used to achieve this condition is termed the ultimate proportional gain (K_u) and the period (T_u) of the oscillation resulting from that gain must be measured. The PID controller settings are then calculated from K_u and T_u using the Ziegler-Nichols tuning relations. The Z-N tuning relations were empirically developed to provide $\frac{1}{4}$ decay ratio.

This classical approach and method most widely used in practice for establishing appropriate values for the control parameters of a PID controller is the Ziegler Nichols tuning method [23]. Based on these two values (i.e. K_u and T_u) and some standard formulae (Table 2:1), all of the controller parameters can be determined. In the Zeigler - Nichols formulae for the closed loop tuning method, as summarized in the table below, the ultimate proportional gain is shown as K_u while T_u is the period of the closed loop system response using that particular ultimate proportional gain value. The Z-N relations are:

Table 4.1: Ziegler-Nichols tuning formula for a closed loop system

Type of Controller	P	PI	PID
Proportional, K_P	$0.5K_u$	$0.45K_u$	$0.6K_u$
Integral, K_I	-	$1.2K_P/T_u$	$2K_P/T_u$
Derivative, K_D	-	-	$K_P \cdot T_u/8$

The value of gain that is used to achieve this condition is termed as ultimate proportional gain with value ($K_u=12.6$) at the period ($T_u= -14.6$). Based on Table 4.1 proportional gain $K_p = 7.54$, integral gain $K_i = -1.03$ and derivative gain $K_d = 13.76$

4.2. Fuzzy logic controller

The form of advanced control scheme which has been considered in this research study is a flexible non-model-based intelligent control approach applied to the pH neutralization process using a Fuzzy Logic Controller. The structure of this controller involves the same structure that is feedback control.

4.3. Control System Structure

There are two important input variables that have a major influence on the control of neutralization process. These are the flow rate for the acid and the concentrations of both solutions. Figure 4.2 shows the block diagram or structure of the overall control system that has been considered in this research. The feedback control is included to reduce or eliminate the error between the pH value in the reactor tank and the desired value which is set by the operator.

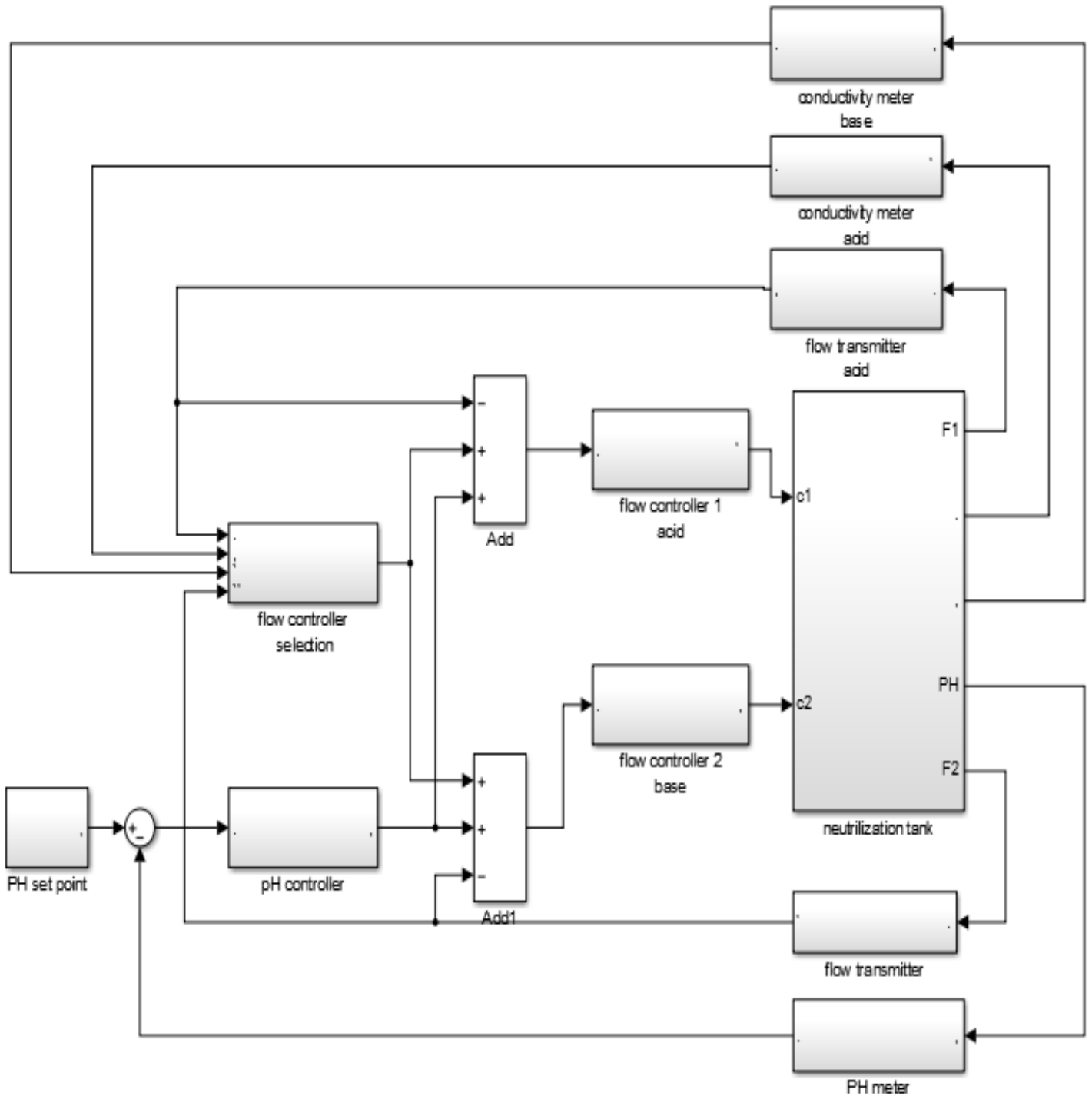


Figure 4.2: An overview of the controller structure proposed

As shown, in the figure 4.2 there are three dedicated controllers that have three different responsibilities. The figure also shows that there are five process values that are recorded from the pH neutralization plant. The process value from the pH Meter provides the pH value from the reactor tank while the Flow Transmitters and Conductivity Meters provide the flowrate and

conductivity readings, respectively, for both the acid and the alkaline. Generally, the main purpose of the flow controllers is to control the amount of each solution flowing into the reactor tank. The pH neutralization controller controls the pH value in the reactor according to the desired value.

The Flow Controller 1 is assigned to manage the amount of acid flow into the reactor tank depending on the reading of the pH value in the neutralization tank. The controller will ensure that the amount of acid flow will be as close as possible to the required set point. As the amount PH value increases the amount of alkaline flow will also decrease. This will eventually increase the amount of the final product in the reactor tank. The amount of acid flow thus provides important information for determining the set point for the Flow Controller 2 and will also act as a load to the neutralization process in the system, depending on the set point for the pH. The amount of the final product from the neutralization tank will also depend directly on this flow rate. Therefore it is appropriate to have flow controllers will be selected by the controller selector depending on the PH reading of the neutralization tank for both the acid and the alkaline flow.

In addition to the amount of acid, the concentrations of both the acid and alkaline solutions are also important for determining the set point for the alkaline flowrate as shown in the block diagram. Theoretically the concentration of both solutions will be a constant value throughout the process as the preparation of the solution is based on a batch process. However, due to practical issues that can arise during the preparation of the solutions, the concentration value is usually not precisely the same as the expected value. In addition to that, the concentration of the solutions might change slightly over a period of time from the original value. This condition might be due to some other reaction in the tank. The alkaline solution is particularly prone to concentration changes as it can precipitate over time. Due to this situation, it is important to monitor the concentration value and use this as a variable in the system rather than just assuming it to have a constant value.

This is done by controlling the amount of alkaline flowing into the tank. For this particular situation the pH value in the neutralization tank will remain the same as the current value and should be the same as the pH set point value. If there is any pH value variation between the current pH value and the set point value for pH, the pH controller will react and change the set point for the alkaline flow to some other value. This control approach can be considered

as a form of cascade control. As clearly shown in the figure 4.2, in addition to the output of the set point calculation block, the set point for the Flow Controllers also depends on the output variable of the other controller. In this case it is the output from the pH controller.

4.3.1. Structure of a Fuzzy Controller

The basic configuration of a Fuzzy logic controller (FLC) has been described by Lee in the survey paper discussed earlier [21]. There are four principal components in a FLC as shown in Figure 4.3. These components are a Fuzzification interface, an inference engine (or decision making logic), a knowledge base and a defuzzification interface. The functions of these are discussed briefly below.

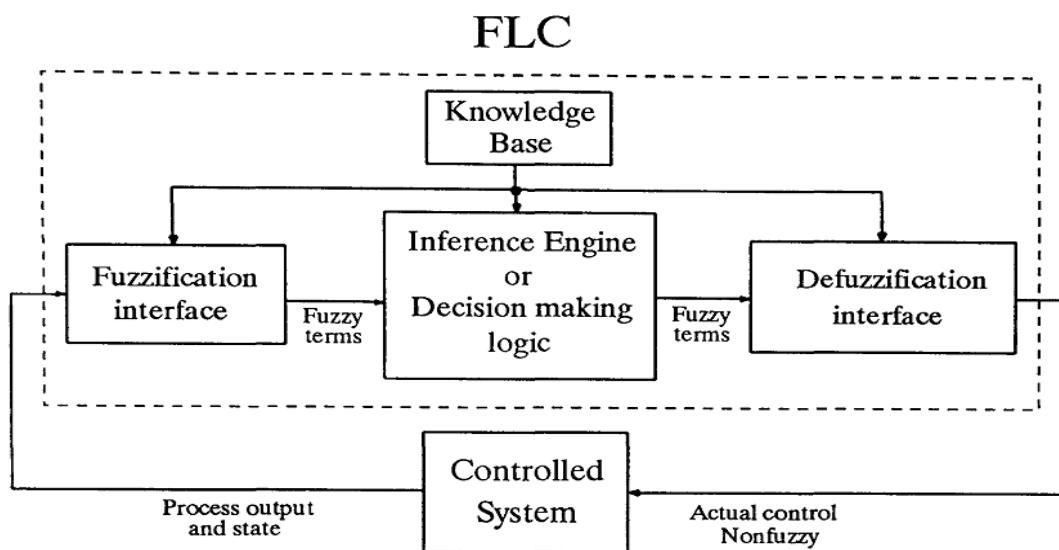


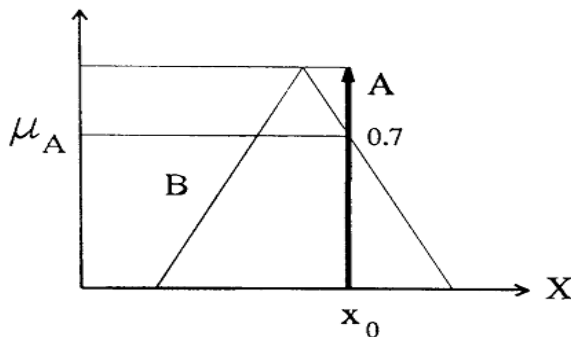
Figure 4.3: Basic configuration of a fuzzy logic controller (FLC) [21]

I. Fuzzification strategies

Fuzzification could be defined as a mapping from an observed input space to fuzzy sets in a certain input universe of discourse. The data manipulation in an FLC is based on the fuzzy set theory, however, in control applications the observed data are usually crisp values. Therefore, Fuzzification is necessary at an early stage. The variables pH, set point and percentage of opening are selected for Fuzzification. In this section, the action performed is obtaining a value of the input variable and finding the numerical values of the membership function defined for that variable. As a result of Fuzzification, the situation currently sensed (input) is converted into such a form that, it can be used by the inference mechanism to trigger the rules in the rule base.

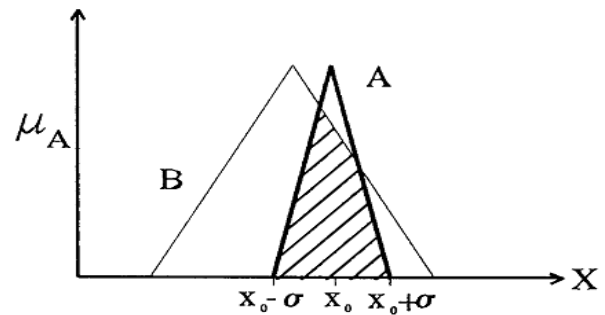
Fuzzification is normally achieved in one of two ways. Its results are shown in Figure 4.4(a) and (b). Both cases show an ordinary fuzzy set B intersecting with a fuzzy set A. A is a fuzzy set coming from the input signal X_0 after fuzzification. In Figure 4.4 (a), A is a singleton but in (b) A is a triangular fuzzy set. The two fuzzification methods are

- i. A crisp value of some input variable can be viewed as a fuzzy singleton within its universe of discourse. In this case a crisp input X_0 will look like a fuzzy set A, with the membership function $\mu_A(X)$ that is equal to zero everywhere but at the point X_0 , where $\mu_A(X_0)$ is equal to one as shown Figure 4.4 (a). The advantages of this approach is that no processing is required for fuzzification in this case. This strategy has been widely used in fuzzy control applications, since it is very easy to implement.



(a) Fuzzy singleton A

α =standard deviation.



(b) Triangular fuzzy set A

X_0 =mean value.

Figure 4.4: methods of fuzzification: The measured data are (a) converted to a fuzzy singleton. (b) Converted to a triangular fuzzy set [24].

- ii. In many applications the observed data are disturbed by random noise. In this case, it is more appropriate to choose an isosceles triangle as the fuzzification function. The vertex of this triangle corresponds to the mean value of a data set, while the base is twice the standard deviation of the data set. Then, we can use this fuzzy number for control manipulation. Figure 4.4 (b) shows the second method of fuzzification. The fuzzy set A with its vertex at X_0 and having the base width equals to 2α is the resulting triangular set. The point X_0 is the mean value and α is the standard deviation of the measured data set.

II. Rule base

Rule base stores the different rules that are to be fired or used according to the inputs. These rules are either gathered from experienced human operator or from careful study of existing PH systems. The base represents the control strategy employed in the PH control.

III. Inference mechanism

The inference mechanism employed in pH control is based on individual rule firing. In this scheme, contribution of each rule is evaluated and overall decision is derived. During inference process, each rule that is fired by a crisp value of pH is summed up after giving the weightages decided by the fuzzification unit. This weightage is called degree of satisfaction (DoS). DoS is decided by the fuzzification module. In the inference mechanism, depending on which all fuzzy sets the input belongs to, the corresponding rules are fired.

IV. Defuzzification strategies

In many practical applications a crisp control action is required to drive the system. Therefore, defuzzification is needed to produce a non-fuzzy control action which best represents the possibility distribution of the inferred fuzzy control action. In other words, the defuzzification process is a mapping between a space of fuzzy control actions defined over an output universe of discourse, and a space of non-fuzzy control actions. There are several kinds of defuzzification strategies being commonly used. These include the maximum criteria, the mean of maximum and the center of area methods.

(a) The maximum criteria method: this method produces the point at which the possibility distribution of the control action reaches a maximum value.

(b) The Mean of Maximum Method (MOM): The MOM strategy generates a control action which represents the mean value of all local control actions whose membership functions reach the maximum. In the case of a discrete universe, the control action will be expressed as

$$z_o = \sum_{j=1}^n \frac{w_j}{n} \quad (4.2)$$

Where w_j is the support value at which the membership function value $\mu(w_j)$ reaches the maximum, and n is the total number of such support values.

(c) The Center of Area Method: The COA method is the most popular method currently being used by control engineers. This strategy generates the center of gravity of the possibility distribution of a control action. The formula is shown below

$$z_o = \frac{\int_z \mu c(z) * z dz}{\int_z \mu c(z) * dz} \quad (4.3)$$

4.3.2. Selection of membership function

Selection of the type of membership function depends, in general terms, on the behavior of the input and output set. Based on the results of a literature survey, most of the fuzzy controllers used in the past for control of the pH neutralization process have used two types of membership function: triangular and trapezoid [23]. Such membership functions are also recognized as the simplest and most commonly used types of membership function in many other control applications. Thus, triangular and trapezoid membership functions were also selected for initial investigations in this application. Both sets, input and output, use the same type of membership function.

There are no specific guidelines in selecting the parameter settings for the membership functions in a fuzzy inference system. Usually the tuning process for parameters is not a straightforward procedure and requires understanding the input and output behavior of the process as well as knowledge of fuzzy logic principles.

4.4. Design and development of the fuzzy inference system

A fuzzy inference system is a process that forms the mapping for the input and output variables using a fuzzy logic approach. This process involves several steps. It usually starts with identifying and defining the boundary of the input and output variables involved (i.e. establishing the relevant Fuzzy Set). This first procedure is quite crucial as the result of this will show the pattern of the input and output sets and provides general ideas about how these variables are linked. This information makes it is easier to move on to the next process, which involves identifying the membership functions for the input and output sets. The simplest and most commonly used membership function is the triangular membership function, which is used in this study. The final process is to develop a set of if-then rule statements. Such statements are used to formulate the conditional statements that comprise the fuzzy logic approach.

As shown in the overview of the control strategy, there are two different types of controller; the flow controller and the pH controller. These controllers are actually both designed using a

fuzzy logic approach. The design for the flow controller will depend on the characteristics of the valve that is controlling the particular stream or flow. The control valve performance will indicate some of the constraints that need to be considered when designing the fuzzy logic controller. Variables such as the operating range, the flow rate for a given control valve opening and the sensitivity of the control valve to electrical inputs will determine the performance of the fuzzy logic controller. In the case of the pH controller, the fuzzy inference system is based on other factors. In addition to the control valve characteristics for alkaline flow, the dynamic reaction of the acid-base neutralization process is of crucial importance in the design. Another important criterion, which needs to be taken into consideration, is the reaction rate. This is a measure of how fast the pH value reacts when a specific quantity of reactant has been pumped into the reactor tank.

4.4.1. Fuzzy Inference System for the Flow Controller

Flow control is used to minimize the variability of wastewater flow rates and composition enter into the equalization basins. Each unit operation in a treatment train is designed for specific wastewater characteristics. Improved efficiency and control are possible when all unit operations are carried out at uniform flow conditions. If there exists a wide variation in flow composition over time, the treatment efficiency of the overall process performance may degrade severely. To dampen these variations, equalization basins are provided at the beginning of the treatment train. So the type of valve used determines the performance of the flow rate.

The type of valve that controls the acid and base streams are assumed an "equal percentage" type valve. The response for the equal percentage type of control valve is much slower and less sensitive compared with the fast opening type of control valve. Thus, designing the fuzzy inference system for a highly sensitive type of control valve is difficult compared with the corresponding task for the less sensitive type of control valve. However a suitable range has been identified from the control valve characteristic curve so that the designed fuzzy logic controller can be utilized for both the acid and alkaline flow control.

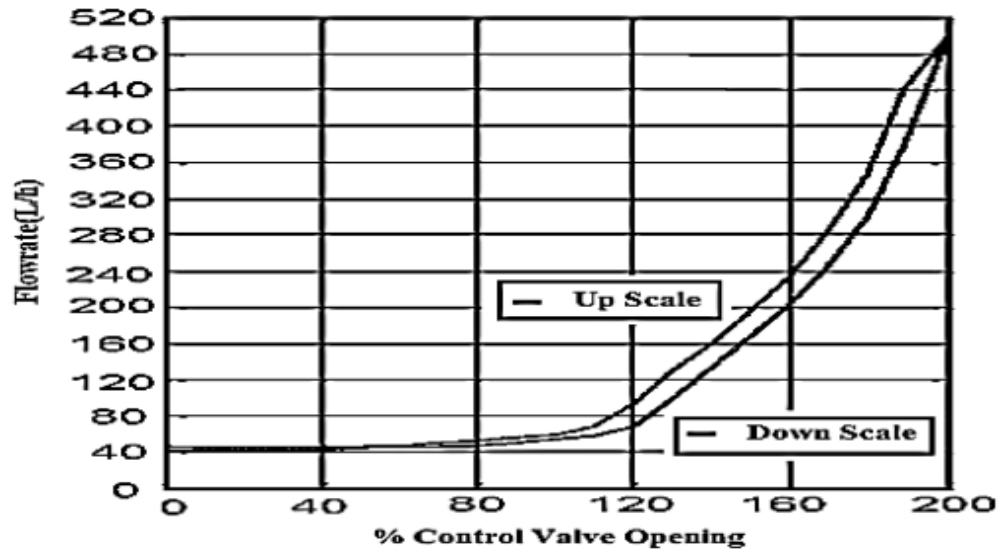


Figure 4.5: Flow-rates of acid and base streams [31]

Figure 4.5 shows the characteristics of both control valves involved on the plant. The characteristics for the valve that is controlling the acid flow, the selected operating range lies roughly between 40% and 120% valve opening.

The input set for the fuzzy logic controller is based on the "error", as shown in Figure 4.6. This error is actually a difference between the set point and the corresponding current value of the relevant process variable. Based on the selected operating range for both control valves, the range for the error that will represent the input set in the fuzzy controller is preferred to be within the range from -100L/h to 100L/h. This range has been selected because the gap between the upper and lower range for acid flow is 100L/h.

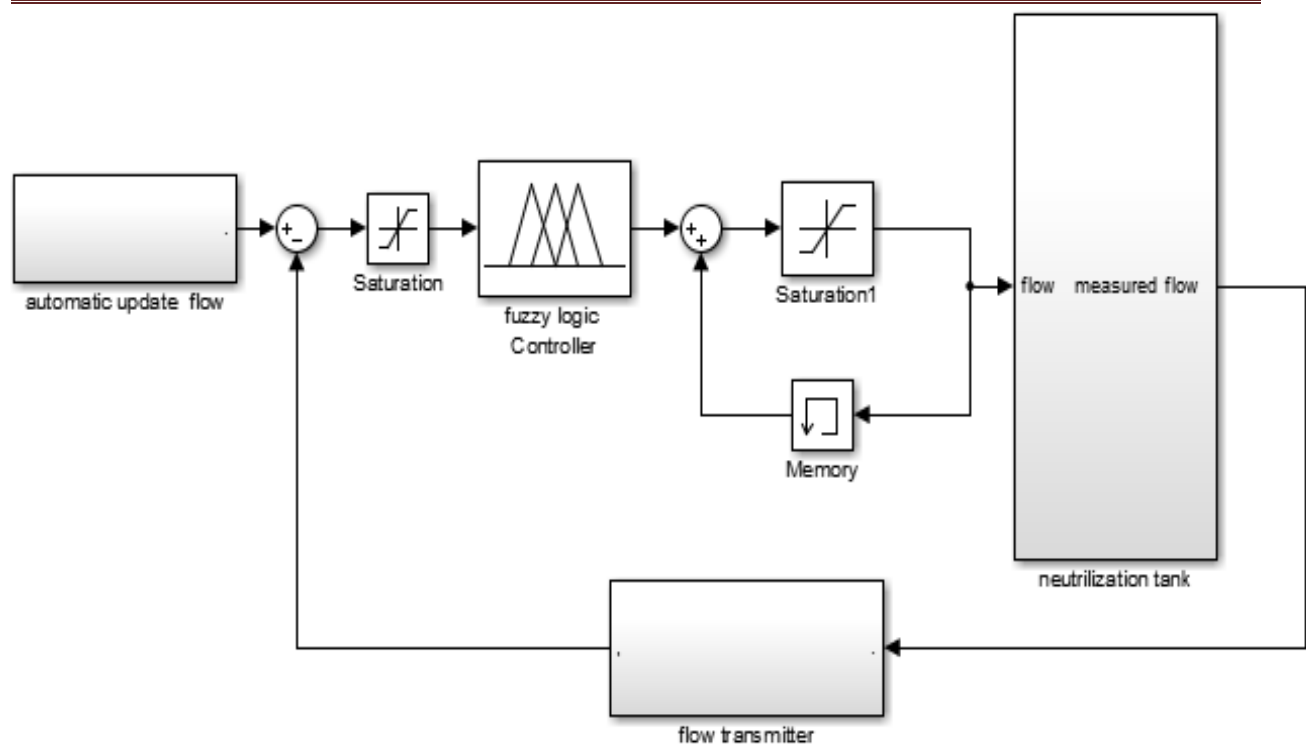


Figure 4.6: Simplified MATLAB/Simulink model representation for the fuzzy logic flow controller

The control valve characteristic curves shows that there is quite a significant change in the flowrate (about 40L/hr) for the acid stream as well as the alkaline stream, for a step change of the control valve opening of around 5%. Therefore it is sensible to choose the output set range for the fuzzy logic controller to correspond to 0% to 2.5% change in valve opening.

It is important to understand the simplified MATLAB/Simulink model before selecting any particular configuration of membership function. This model is used as a basis for the flow controller for the acid as well as for the alkaline stream. Depending on the present error, which is the difference between the set point and the current process value, the fuzzy logic controller will react according. The largest value of error should be 100L/h hence the controller will react with the maximum output involving 2.5% change in control valve opening.

The output from the fuzzy logic controller is termed the manipulated variable which is then sent to the plant as an input signal to the particular control valve. At the same time the present manipulated variable will be stored in the memory block as shown in the figure 4.6. The output from the memory block will also contribute to the variation of the control valve movement or opening.

As shown in the arrangement in Figure 4:6, the memory block will act as an accumulator. When the fuzzy logic controller provides a positive value, the value in the memory block will increase and when it is negative, the value in the memory block will decrease. As the error decreases towards zero the process value gets closer to the desired set point. The output value from the fuzzy logic will also move towards a zero value. At this point the value in the memory block will tend towards a steady state. Finally, the manipulated variable that drives the final movement of the control valve would be obtained from the value in the memory block.

As shown in Figure 4.7, there are eleven groups of membership functions that will represent the input set. This figure also shows that the setting for the input range is between -100L/h and 100L/h. As explained in an earlier paragraph, the input set actually represents the error and this is defined simply as:

$$\text{Error} = \text{Set Point} - \text{Process Variable} \quad (4.4)$$

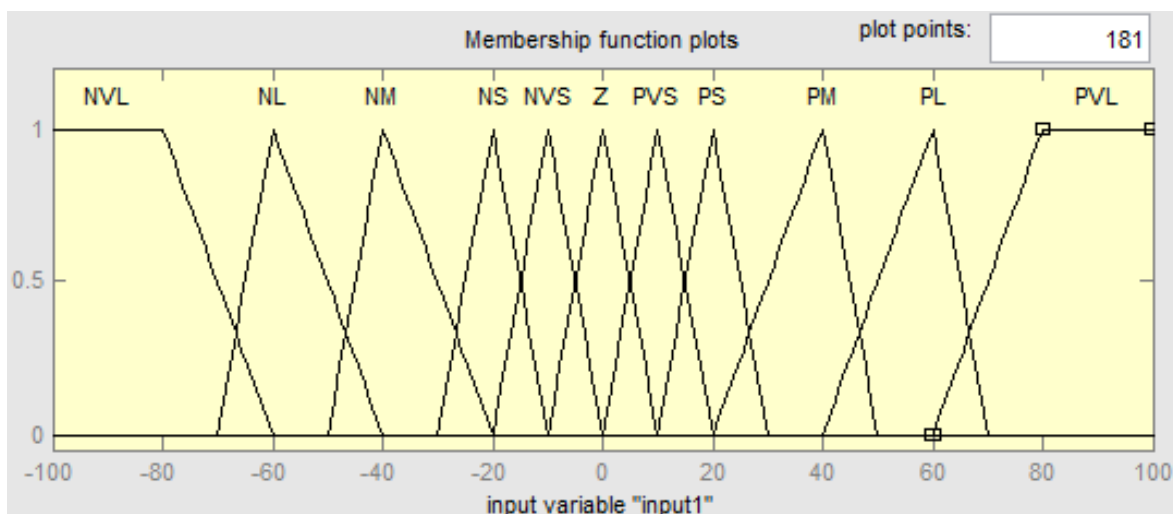


Figure 4.7: Membership function for input set

The center point is when the error is zero and it is clear that the whole range of input can be divided into two regions, one for negative error and one for positive error. The values for the positive error region mirror those of the negative error region.

As mentioned there are no specific rules for configuring the membership function. In this case eleven (11) sets of membership functions have been chosen which were mainly based on the control valve characteristic and some trial-and-error procedures. During this exercise it was observed that grouping the membership function in the central part of the input range, as

shown in Figure 4.7, will ensure that control effort is focused on the specific targeted control range.

Thus, when the error lies between -40L/h and 40L/h the membership functions are very close to each other in order to provide a region in which the response is highly sensitive. This is to ensure that the fuzzy controller will provide a good response with zero steady state error as well as minimum overshoot. Meanwhile the range between 40L/h and 100L/h and also between -40L/h and -100L/h will contribute to the overall system performance by ensuring a reasonably fast rise time, which is another important measure of performance.

Figure 4.8 shows the arrangement of membership functions for the output set. There is a one-to-one relationship between the input set and the output set and there are also eleven groups of membership function for the output set. As shown in the figure the output set range is from -2.5% to 2.5% valve opening.

Since the range for the output set is considerably smaller than that for the input set the arrangements of the membership functions are quite consistent. However, as shown in Figure 4.8, there is no concentrated region unlike the arrangement of the membership function for the input set where the concentrated region is at the center. As in the case of the membership functions for the input set there are also two distinct regions, for positive valve opening and the negative valve opening. The positive valve opening will provide a response for the positive error region whereas the negative valve opening will react appropriately for the negative error region.

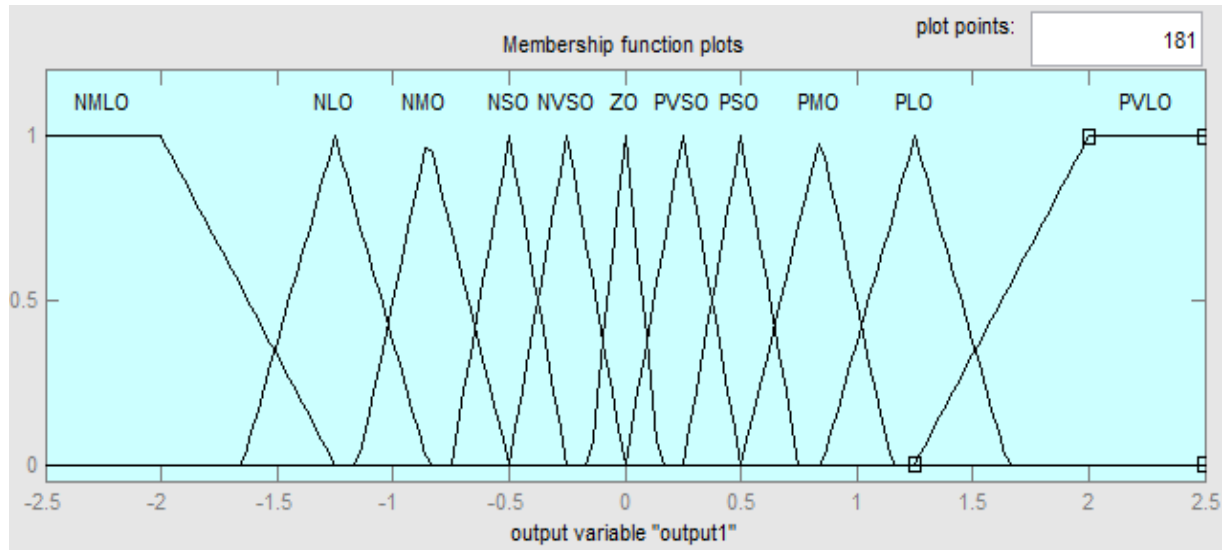


Figure 4.8: Membership function for output set

The choice of parameters for the membership function is also crucial. These parameters will determine whether the output from the fuzzy logic controller is too sensitive to the input set, which then produces a high level of ripple in the output, or are too insensitive and lead to a very sluggish output response. Thus the key performance index of the fuzzy logic controller will also depend on these parameters.

Table 4.2 shows that the relationship between the input set and the output set of the fuzzy logic controller. These if-then rule statements are quite straightforward since this is a one-input one-output case.

Table 4.2: If-then-rules statements for the fuzzy logic controller

No	Statement	Error (L/h)	Statement	Manipulated Variable (% Control Valve Opening)
1	IF	NVL	THEN	NVLo
2	IF	NL	THEN	NLo
3	IF	NM	THEN	NMo
4	IF	NS	THEN	NSo
5	IF	NVS	THEN	NVSo
6	IF	Z	THEN	Zo
7	IF	PVS	THEN	PVSo
8	IF	PS	THEN	PSo
9	IF	PM	THEN	PMo
10	IF	PL	THEN	PLo
11	IF	PVL	THEN	PVLo

Figure 4.9, is a two-dimensional curve that represents the mapping from the input set to the output set. This curve provides an indication of how the fuzzy logic controller will behave or respond when there is a difference between the set point and the measured value from the flow transmitter.

The diagram provides an indication of how the if-then rule statements work. Basically, when the value of error is positive (that is when the value of the process variable is below the set point), the opening action of the control valve should be increased. This action is also in the positive direction, as indicated in Figure 4.9. On the other hand, when the value of error is negative (indicating that the process variable is above the set point), the opening action of the control valve should be decreased. This action is thus in a negative direction as shown clearly in the Figure 4.9. The overall form of the controller is seen to be approximately linear for error values between

-60 and 60 L/h. The main objective for this flow controller is to provide zero error with zero action for the manipulated variable.

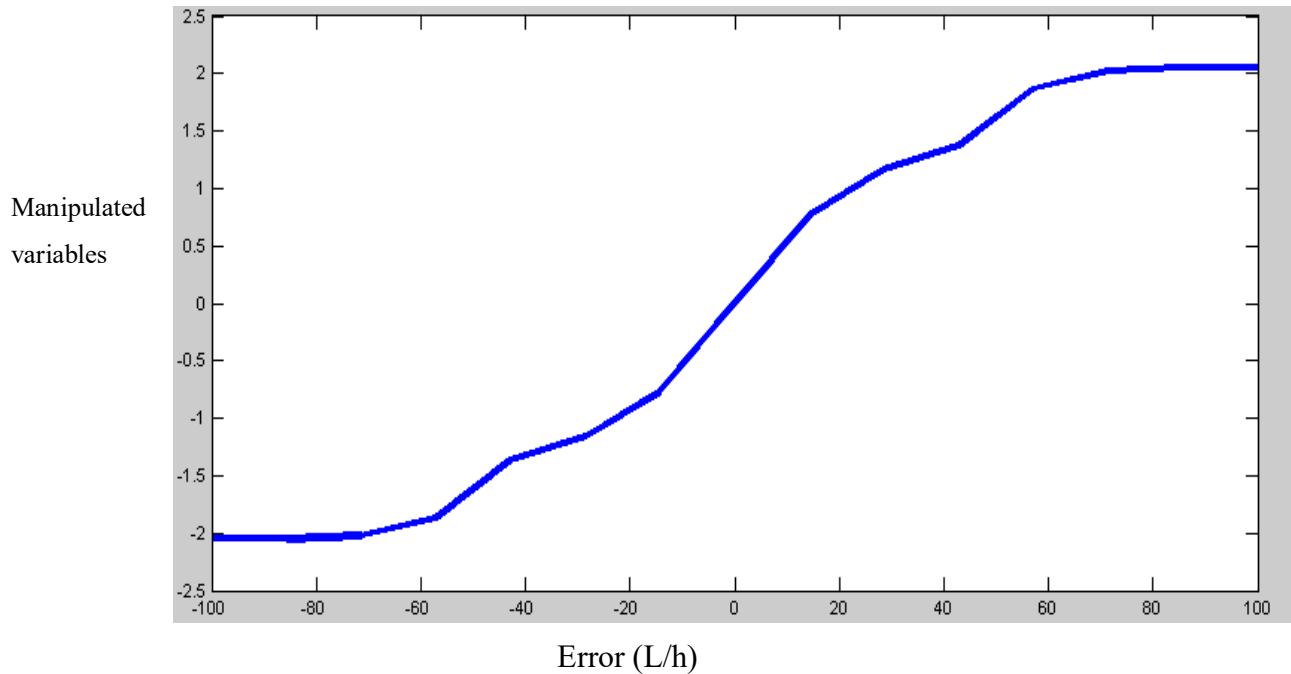


Figure 4.9: The response of the fuzzy logic controller in terms of the manipulated variable as a function of the error

4.4.2. Fuzzy Inference System for the pH Controller

The pH controller will also be responsible for establishing the set point of the flow controller which determines the alkaline or acid flow. In the auto-calculated value for the flow controller will also depend on the variation of the pH value in the neutralization tank with the desired pH set point. When the current pH value is below the desired value the Fuzzy Logic pH Controller will provide a new set point for the Fuzzy Logic Flow Controller. The new value for the set point will depend on the difference between the pH value in the neutralization tank and the desired pH value.

The output set for the controller will correspond to the flowrate of the alkaline stream. The range for the output set is configured to be between -100L/h and 100L/h, which is exactly the same as the input set range for the Fuzzy Logic Flow Controller.

The saturation block that comes before the Fuzzy Logic Flow Controller will limit the error to the range from -100L/h to 100L/h. This block will prevent any value to the fuzzy controller being missed if the error value lies beyond this range. Thus, if the value is over 100L/h the input signal to the controller will be limited to 100L/h.

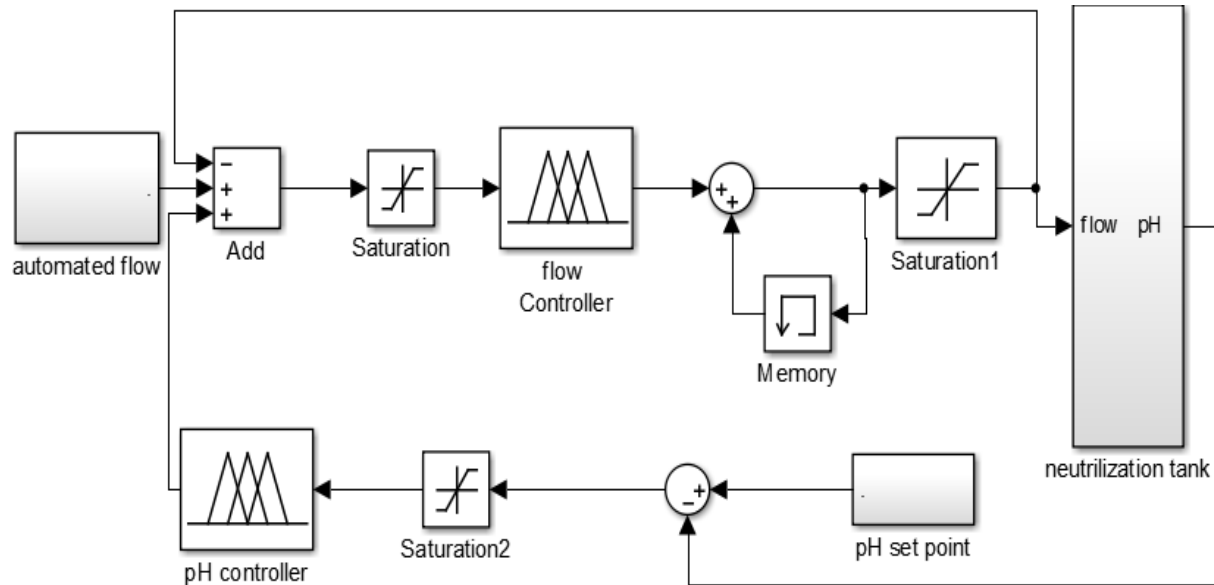


Figure 4.10: MATLAB/Simulink representation for the overall pH controller

This condition will occur when there are variations in both the pH value and the alkaline stream at the same time. Since these variations are inter-connected the controllers will react accordingly and bring the error down to zero. Figure 4.11 shows the membership functions for the input set for the pH controller. Unlike the input set for the flow controller there are nine groups of membership functions that will represent the input set for the pH controller. This is because of the smaller range of the input set compared to the range of the input set used for the flow controller. Thus fewer membership functions are needed to cover the range. A further reason for using a smaller number of membership functions for the pH process is that the dynamics of this process are significantly slower compared to the flow process. Therefore it is less sensitive and requires a smaller number of membership functions.

As in the flow controller the number of membership functions is increased towards the middle point of the range. This critical range will determine the smoothness of the settling condition and to ensure that the zero offset for the steady state is achievable. However the overall system

performance of the fuzzy logic controller will depend on the combination of membership function for the input and output sets.

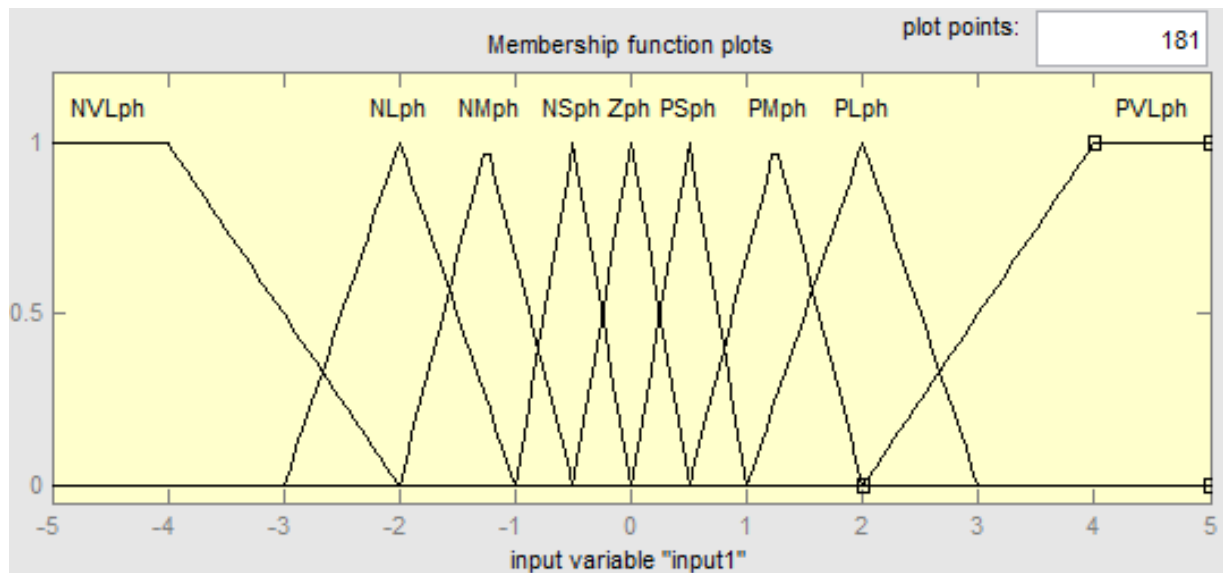


Figure 4.11: Membership function for the input set for the pH fuzzy logic controllers

Figure 4.12, shows the membership functions for the output set of the pH controller and the input and output rule is discussed in Table 4.2. The parameter values in this case were determined from the results of experiments that were designed to establish facts about the process such as the values of flowrate needed to increase or decrease the pH to a specific value and provide a reasonable time response.

As in the case of the input set membership functions, there are also nine groups of membership functions in the output set for pH control. As shown in the figure, the triangular shape of the membership function in the middle of the range is very narrow. This is to cater for small variations of the pH error for conditions below a pH value of one. When this condition occurs the pH controller will then make a small step change of the set point which will then make the control valve react accordingly. If this membership function were too wide it would contribute to poor control performance through introducing features in the response such as a large overshoot, unwanted oscillations or a ripple under nominally steady state conditions. In contrast with this membership function in the middle of the range, the rest of the triangular membership functions are all similar in form and are evenly distributed.

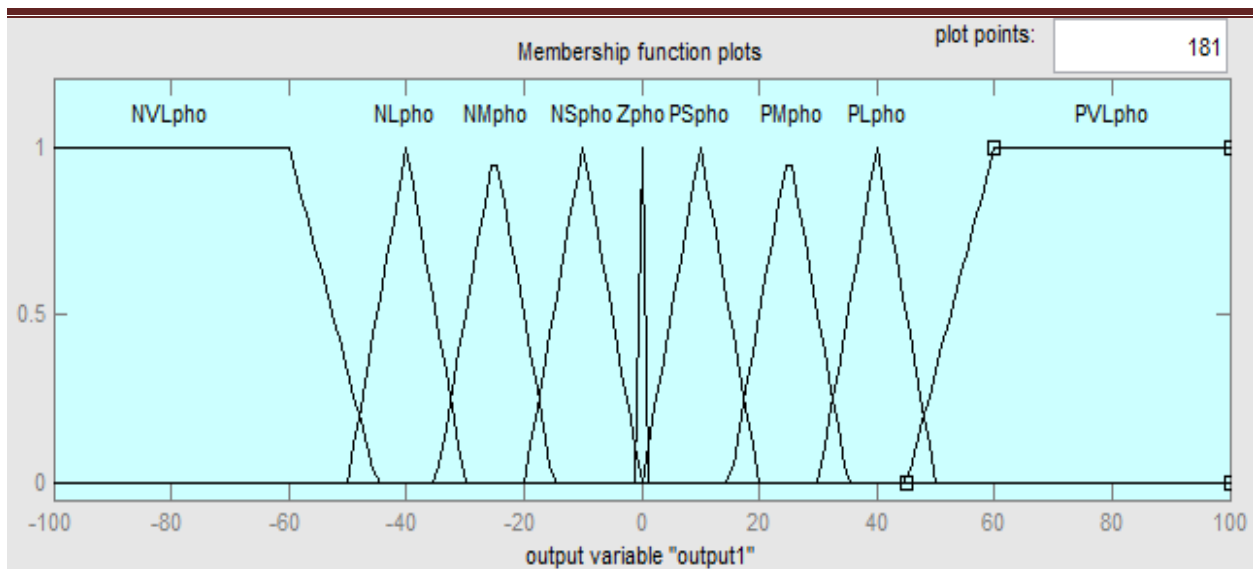


Figure 4.12: Membership function for outputs set for pH fuzzy logic controller

The relationship between the input set and the output set of the pH Fuzzy Logic Controller is given in Table 4.2. Again, the if-then rule statements for the pH controller represent a straightforward process since this is a one-input one-output case as shown in the table. From the result of this fuzzy inference system, a two dimensional curve that represents the overall input and output response of the controller is obtained and is shown in Figure 4.13.

Table 4.3: If-then rule statements for the fuzzy logic controller

No	Statement	Error (L/h)	Statement	Manipulated Variable (% Control Valve Opening)
1	IF	NVLph	THEN	NVLph _o
2	IF	NLph	THEN	NLph _o
3	IF	NMph	THEN	NMph _o
4	IF	NSph	THEN	NSph _o
5	IF	Zph	THEN	Zph _o
6	IF	PSph	THEN	PSph _o
7	IF	PMph	THEN	PMph _o

8	IF	PL _{ph}	THEN	PL _{ph_o}
9	IF	PVL _{ph}	THEN	PVL _{ph_o}

Figure 4.13, is a two-dimensional curve that represents the mapping from the input set to the output set. This curve provides an indication of how the fuzzy logic controller will behave or respond when there is a difference between the set point and the measured value from the pH value.

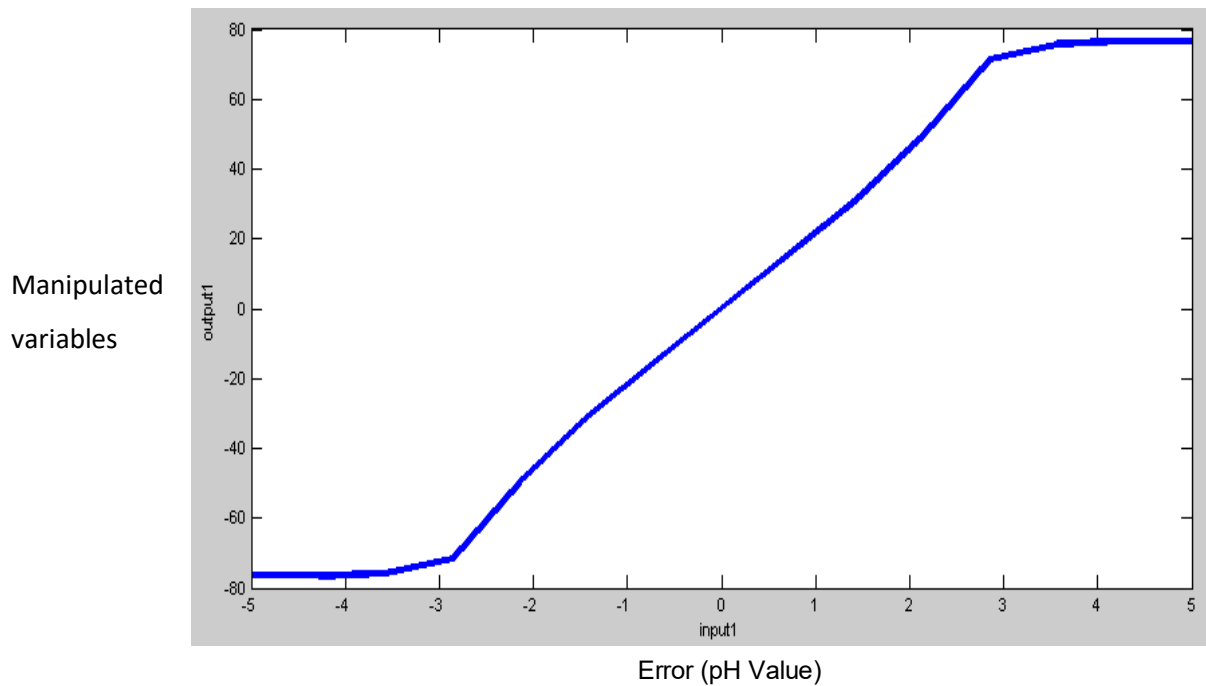


Figure 4.13: The response of the pH fuzzy logic controller

The diagram provides an indication of how the if-then rule statements work. Basically, when the value of error is positive (that is when the value of the process variable is below the set point), the opening action of the control valve should be increased. This action is also in the positive direction, as indicated in Figure 4.13. On the other hand, when the value of error is negative (indicating that the process variable is above the set point), the opening action of the control valve should be decreased. This action is thus in a negative direction as shown clearly in the Figure 4.13. The overall form of the controller is seen to be approximately linear for error values between -3 and 3 PH value. The main objective for this pH controller is to provide approximately zero error with zero action for the manipulated variable.

5. RESULT AND DISCUSSION

This chapter discusses the results obtained using the computer Simulink programs, these results are for different control strategies (PID and fuzzy logic controllers). This section also describes the performance of the developed PID and fuzzy logic controllers when applied to the pH neutralization model plant. A number of simulations performed to investigate the robustness of the system are discussed.

The main idea of this section is to discuss the feasibility and reliability of the control strategy. This section also describes the performance of the developed PID and fuzzy logic controllers when applied to the pH neutralization in wastewater treatment plant. The main objective of the process is to maintain the pH value in the set point. The servo response, the tracking efficiency and the disturbance rejection behavior of the controller is discussed in this section. All of these results are based on the control strategy described previously.

5.1 Dynamic Behavior

In this section, the dynamic responses are studied for different step changes in the manipulated variable (F_b) in order to study the effect of each change on the controlled variable pH. These changes are: (25%, 50%, and 75%) step change in the base flow rate (F_b). The effect of the base flow rate (F_b) on the pH is shown on Figure (5.1).

In this simulation study, it is assumed that the wastewater is acidic in nature with an acetate acid concentration of $C_a = 0.09$ M and flow rate of $F_a = 17$ L/min. An initial amount of wastewater, $V_0 = 250$ l, of the concentration of alkaline (0.0067 M) already present in the tank and the wastewater stream, F_a , will be neutralized simultaneously with alkaline solution of concentration C_b and flow rate F_b . The base flow rate, F_b , is set so as to simulate the maximum flow capacity through the control valve. However, during control, the F_b can be between zero flows to maximum F_b as it is being manipulated by the controller. These values were chosen because they are typical values for a neutralization process of this kind.

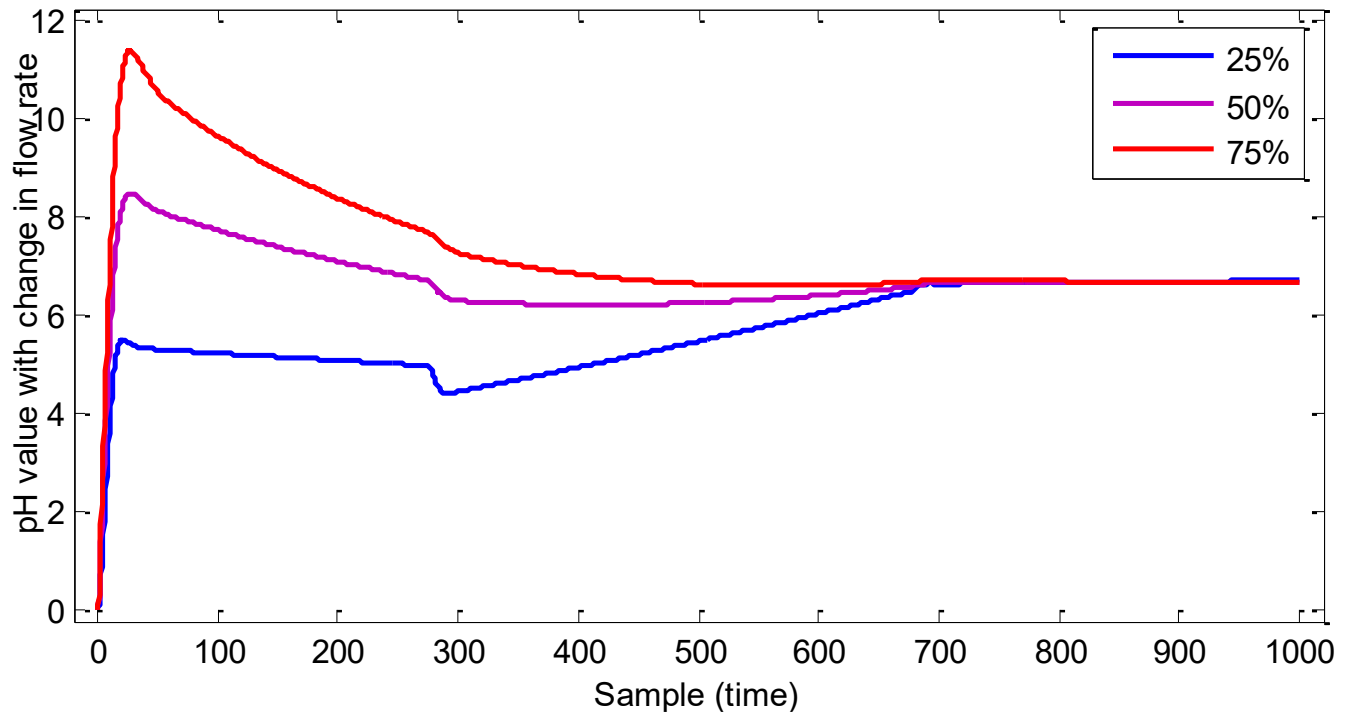


Figure 5.1: Open Loop Response of pH Neutralization Process with different percentage of alkaline flow rate

From Fig 5.1 it can be seen that the increase in the base flow rate (F_b) is not directly proportional to pH for different steps in the base flow rate (F_b).

5.2 Comparison between Controllers' Settings Techniques

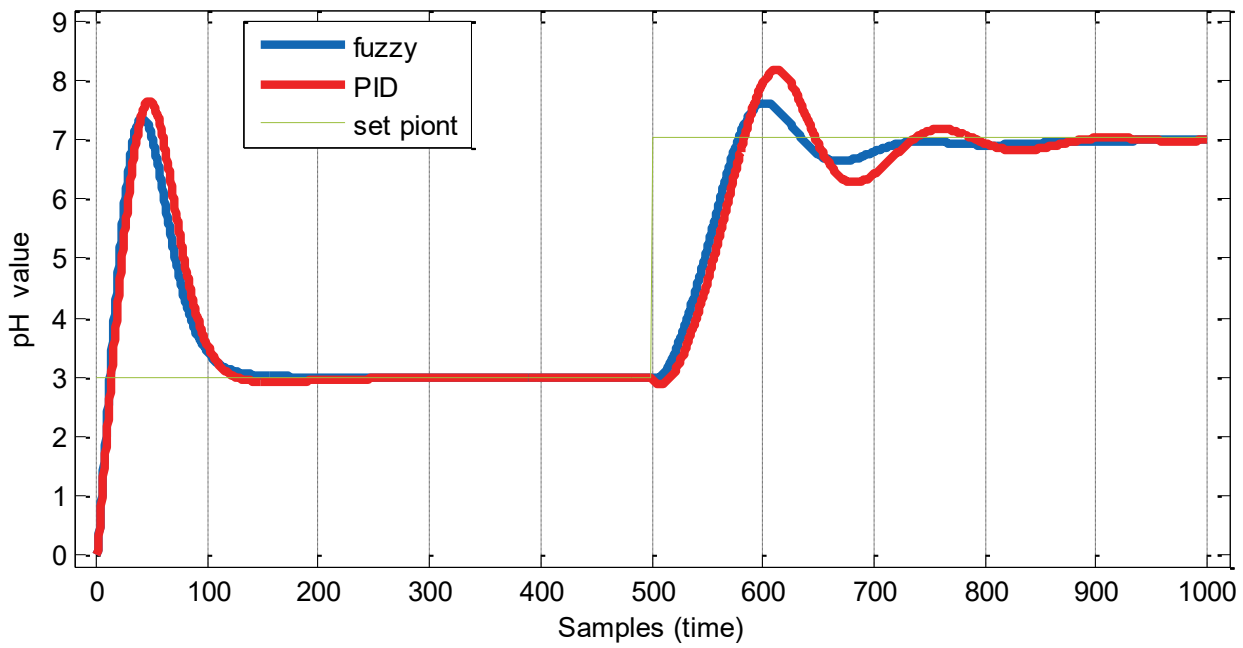
The control objective for most pH systems, such as wastewater neutralization, is regulation of the pH subject to flow and concentration disturbances, and hence, the control of the pH process has been studied as a regulatory problem. It is also necessary to make set point changes to a process, and hence, the set point tracking performance of the control system is relevant for PID and fuzzy controllers.

5.2.1. Set point tracking

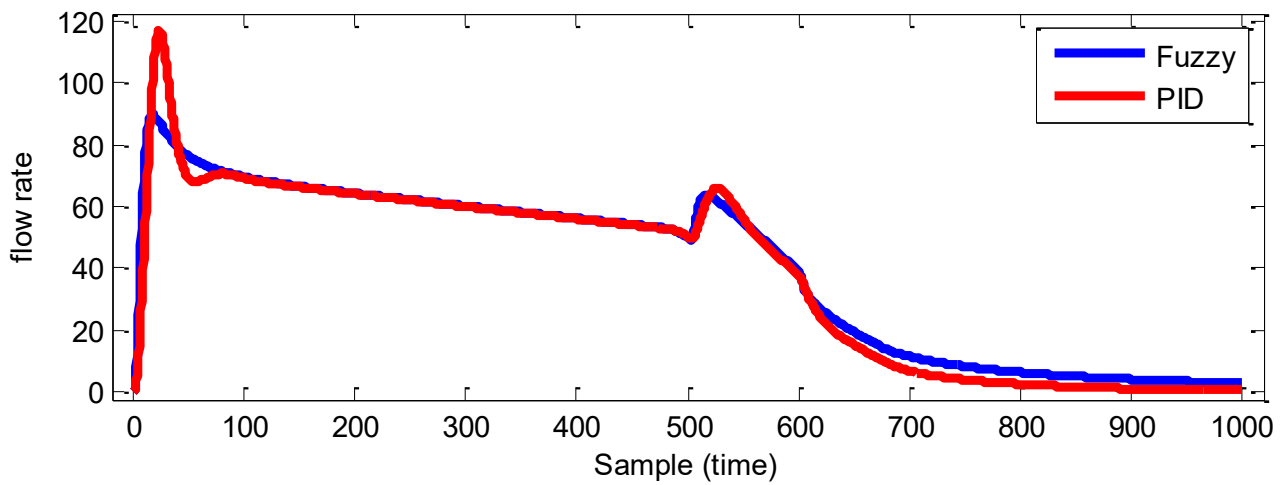
We noted in chapter two section 2.3 that the control of pH is very difficult due to the non-linear relationship between pH and concentration. In the following simulation test the PID controller and

fuzzy logic controller for set point changes. A sampling range from 0 to 500 for the first, 500 to 1000 for second samples are used for the tests in all the following simulation runs.

(a) set point change



(b) flow rate of alkaline



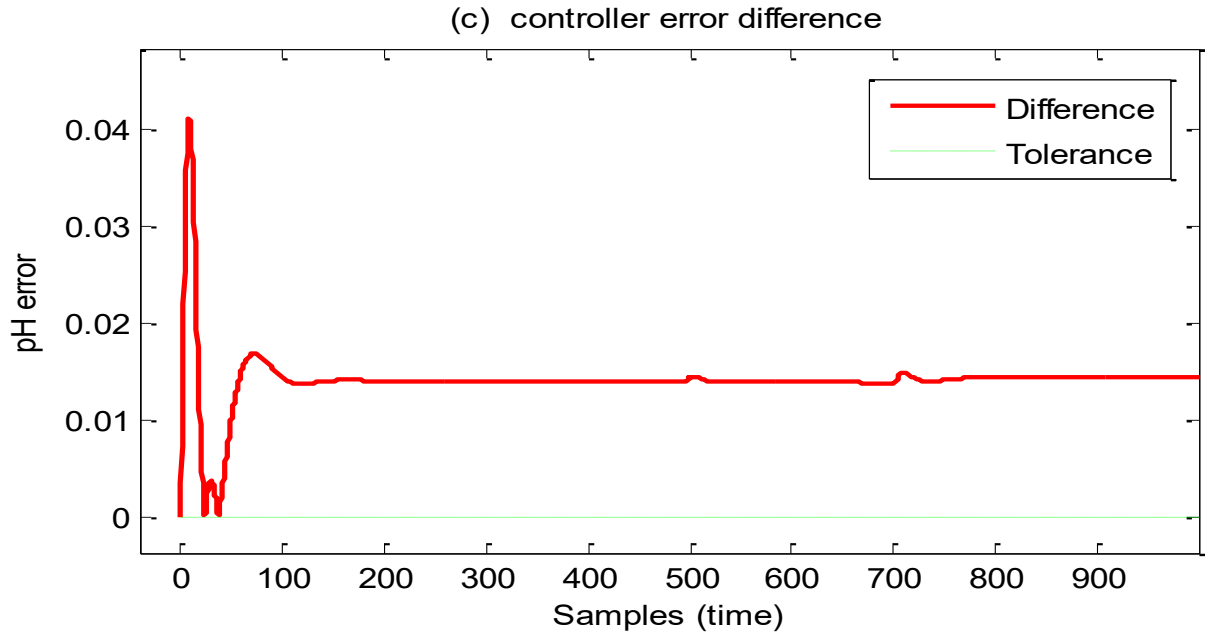


Figure 5.2 : Set point Tracking Response of PID Controller and fuzzy logic controller for the pH Neutralization Process.

The flow controller set point for the acid stream was set at 15L/MIN and two step-changes were made for the pH value in the neutralization tank. The first change was made from pH value 3 to pH value 7 and the second set-point change was a change in the positive direction to pH value 7.

As shown in the figure 5.2, the controllers are able to respond to the two instances of set point changes. The major difference between the PID pH controller and the Fuzzy logic of the pH controller is in terms of the behavior of the control valve that is controlling the alkaline stream. The control valve movement for steady state conditions is more active at pH value 7 compared to pH value 3. This obvious difference is due to the effect of the new pH fuzzy logic controller.

As shown in the figure, the responses at the critical region are unsatisfactory, When using a conventional PID controller to control the process near to the, the pH output often oscillates around the set-point with a large over-shoot and a very long settling time as shown in Figure 5.2. The objective of this simulation is to observe the control performance of the PID and fuzzy logic controllers when a set point change has been introduced. However the fuzzy controller makes the process near to the, the pH output near to the set-point with a little over-shoot and a very small settling time. Also, as show the flow rate for the alkaline stream fluctuates more on PID control than the fuzzy response.

The simulation result shown in Figure 5.2 (c) has demonstrated the pH deference between the controllers clearly shows the effectiveness of the of the pH fuzzy logic controller within the critical region. The fuzzy pH controller immediately takes an appropriate action to recover from the excess alkaline by bringing the alkaline flow rate down. Because of this recovery action there is a slight overshoot which takes the pH value to its set point value. Also when compared to classical PID scheme, fuzzy gives minimum ISE value. The complete performance analysis of PID and fuzzy control scheme such as time domain specifications, performance indicator and total computational time is tabulated in Table 5.1.

Table 5.1: Set point Tracking - Comprehensive Performance Analysis of all Closed Loop Configurations for pH Neutralization Process

Control Schemes	Overshoot (%)	Settling Time (Sec)	Set point (pH)	Average Integral Square Error (ISE)
PID	6.5	97.8	3	5.10
	4.056	368.5	7	
Fuzzy	4.6	36.23	3	3.19
	2.8	236	7	

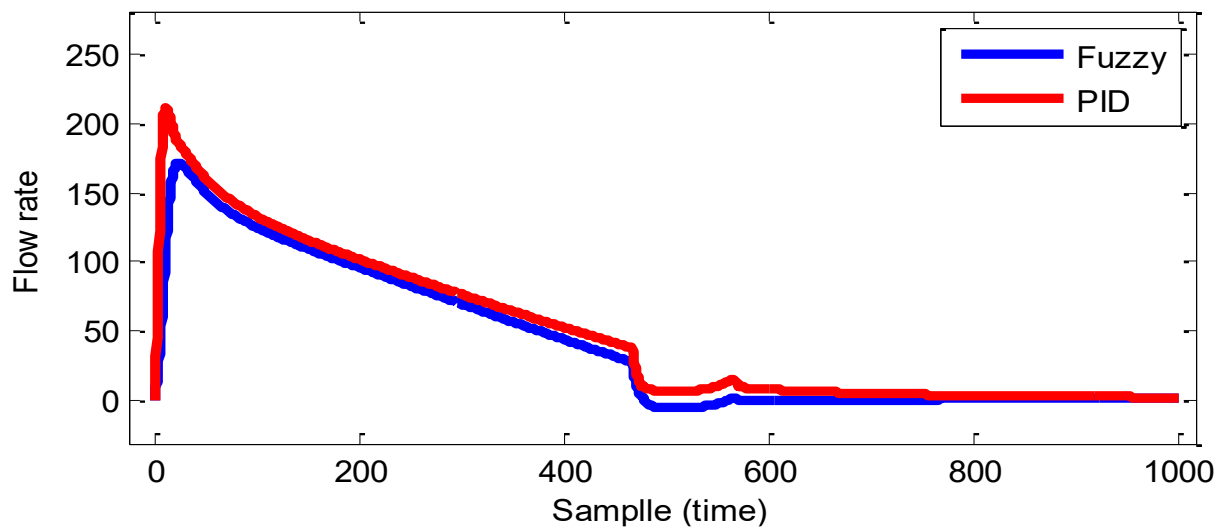
Table 5.1 shows The FLC reduces the ISE by almost 38.38%. Both controllers show almost equal maximum overshoot when process is subjected the nominal process parameters. Finally the FLC reduces the settling time by more than 14.1% in comparison with PID.

5.2.2. Disturbance rejection performance

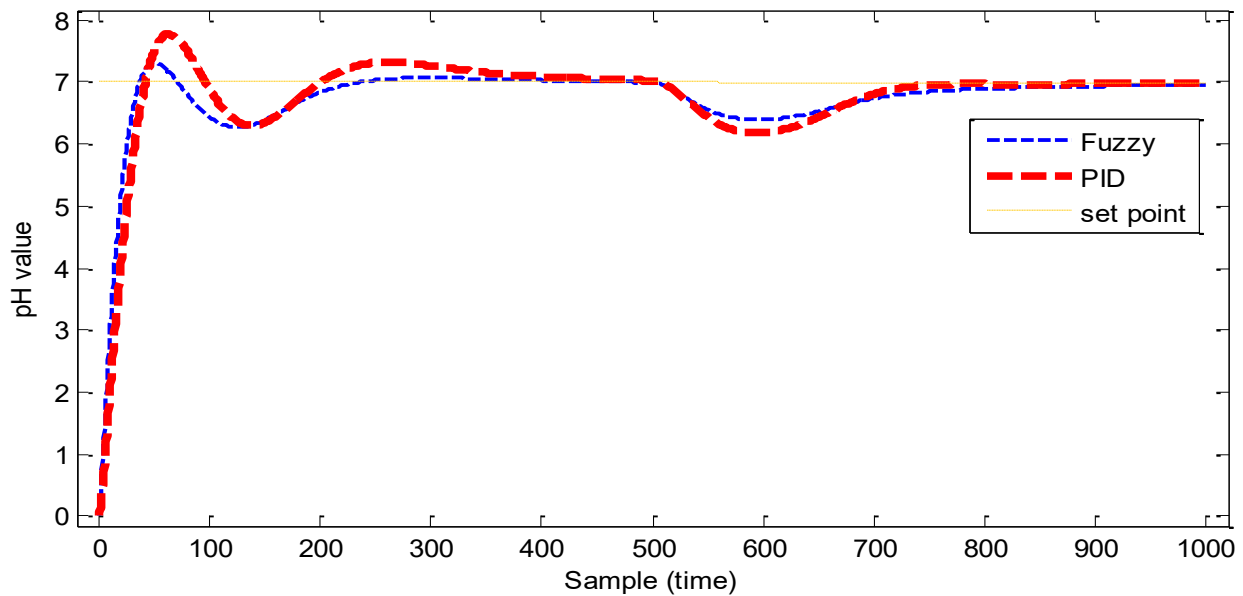
In the study of disturbance rejection we have to consider two main process variables. These are the flow rate and the concentration of acid and alkaline streams. In the following we examine the controller performance for rejecting upsets in process load variables such acid flow rate or acid concentration of the feed stream. The process and controller parameters used in the previous test are also utilized here unless otherwise mentioned. In this simulation result, the regulatory

performance was investigated on pH process, where the perturbations in base flow-rate in a range $\pm 30\%$ from nominal value were applied.

(b) alkaline flow



(a) disturbance rejection



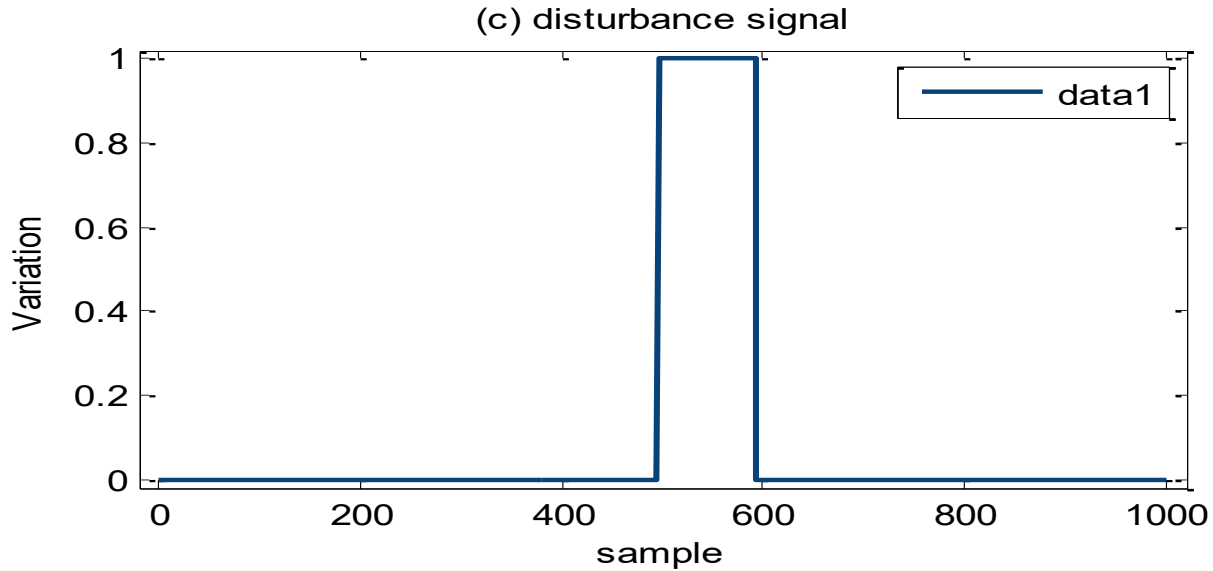


Figure 5. 3: Base flow rate Disturbance Rejection Response of PID Controller and fuzzy controller in pH Neutralization Process.

Figure 5.3 depicts the closed-loop response to set point change using the same parameters and process operating conditions utilized previously. In this case the flow controller takes about 10 seconds to reach and settle to the new set point. Thus this 10 seconds of delays causes a significant amount of alkaline to reach the reactor tank. This additional amount of alkaline generates a slightly higher pH value than the average pH value. As shown in the figure the fuzzy pH controller immediately takes an appropriate action to recover from the excess alkaline by bringing the Figure alkaline flowrate down than PID controller. Because of this recovery action there is a slight overshoot which takes the pH value to its set point value. This form of transient can be improved further with some minor adjustments to the fuzzy logic pH controller.

The PID controller shows a high oscillation and overshoot when the flow disturbance affects the process. This can be attributed to the conservative set of tuning parameter used to keep stable the process. However, if the PID tuning parameters are readjusted to perform a fast response to the disturbance, when the second set point change affects the process, the control loop as shown in Figure 5.3, the final simulation result shows the capability of the fuzzy logic controllers when there are disturbances in the flow rate of the acid solution. Again the idea of this exercise is to observe

whether or not the fuzzy logic controls are able to maintain the pH value at pH value to the set point regardless of the disturbances in the concentration of the acid solution.

The fuzzy controller shows good disturbance rejection performance, as compared to PID controller can be seen in Fig.5.3 when the process is facing to flow rate disturbance. The complete performance analysis of PID and fuzzy control scheme such as time domain specifications, performance indicator and total computational time are tabulated in Table 5.2.

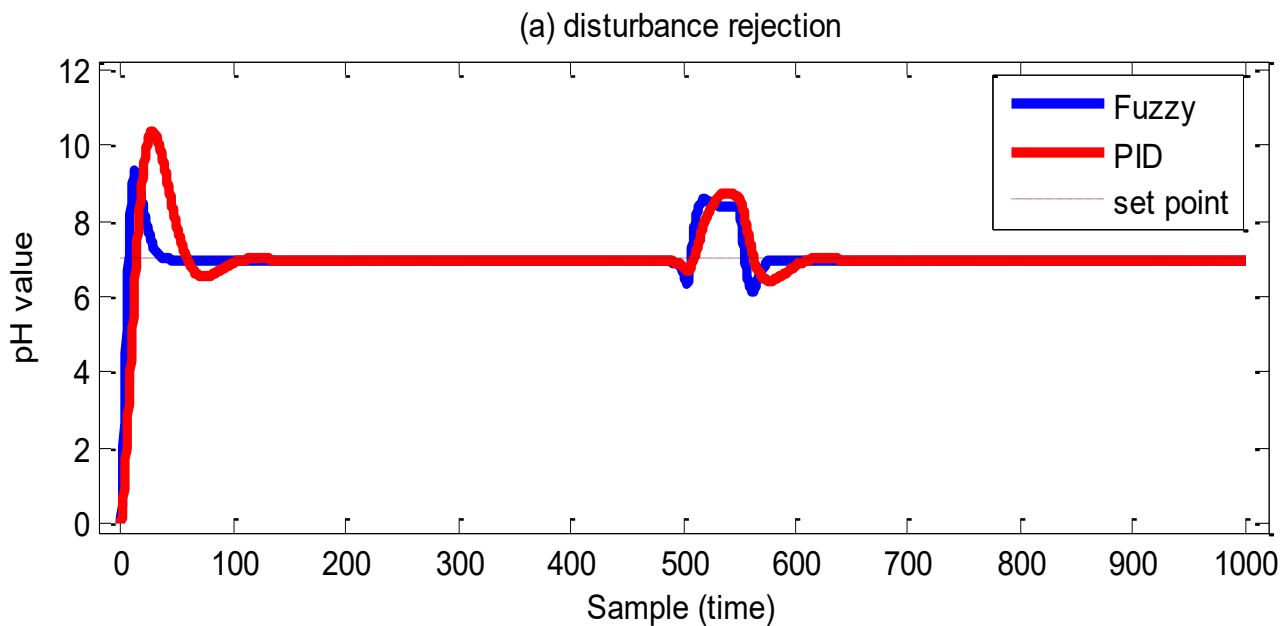
Table 5.2: base flow rate Disturbance Rejection – Comprehensive Performance Analysis of all Closed Loop Configurations for pH Neutralization Process

Control Schemes	Over shoot (Sec)	Time taken to anticipate the disturbances (sec)	Set point (flow rate)	average Integral Square Error (ISE)
PID	4.67	60.56	3	3.67
	1.67	285	7	
Fuzzy	3.74	51.32	3	2.25
	1.87	263	7	

The FLC reduces the ISE by almost 22.46%. And also maximum overshoot and the settling time reduces by 23.3% and 5.62% respectively in comparison with PID controller when process is subjected to disturbance 20% of alkaline flow rate.

5.2.3. Robustness

The controller should be able to react to other disturbances such as concentration and flow variations without any retuning work. The aim of this exercise is to investigate the robustness of the fuzzy logic controller for a series of process variables changes. We have to consider two main process variables. These are the flow rate and the concentration of acid streams. In the figure 5.4 shows the controller performance when changes in the acid stream flow rate affect the process as disturbance. At time 0 and 500 the acid stream flowrate increases 20%. The fuzzy controller tracking for set point faster and rejecting concentration disturbance effectively, keeping the neutralization process at set point. In these case The PID controller also shows a high oscillation and overshoot when the flow disturbance affects the process as we see the performance parameter change in table 5.3. However, if the PID tuning parameters are readjusted to perform a fast response to the disturbance, when the second set point change affects the process, the control loop as shown in Figure 5.4.



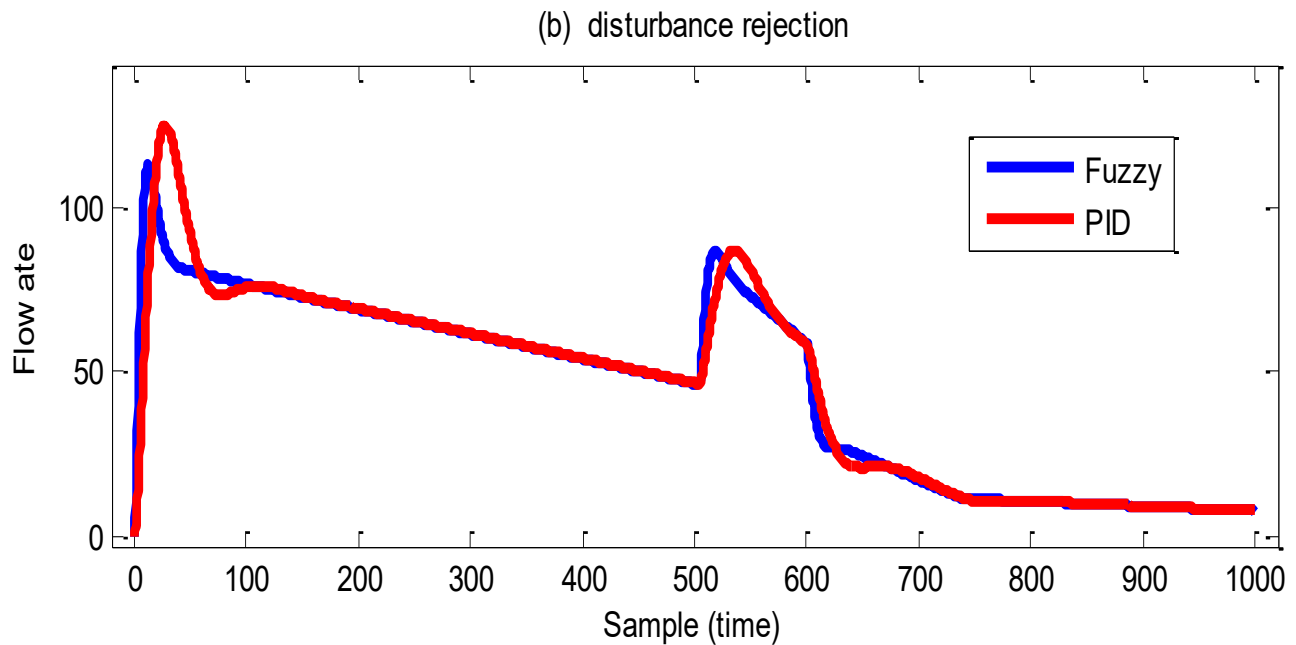


Figure 5.4: acid flow rate Disturbance Rejection Response of PID Controller and fuzzy controller in pH Neutralization Process

The complete performance analysis of PID and fuzzy control scheme such as time domain specifications, performance indicator and total computational time are tabulated in Table 5.3.

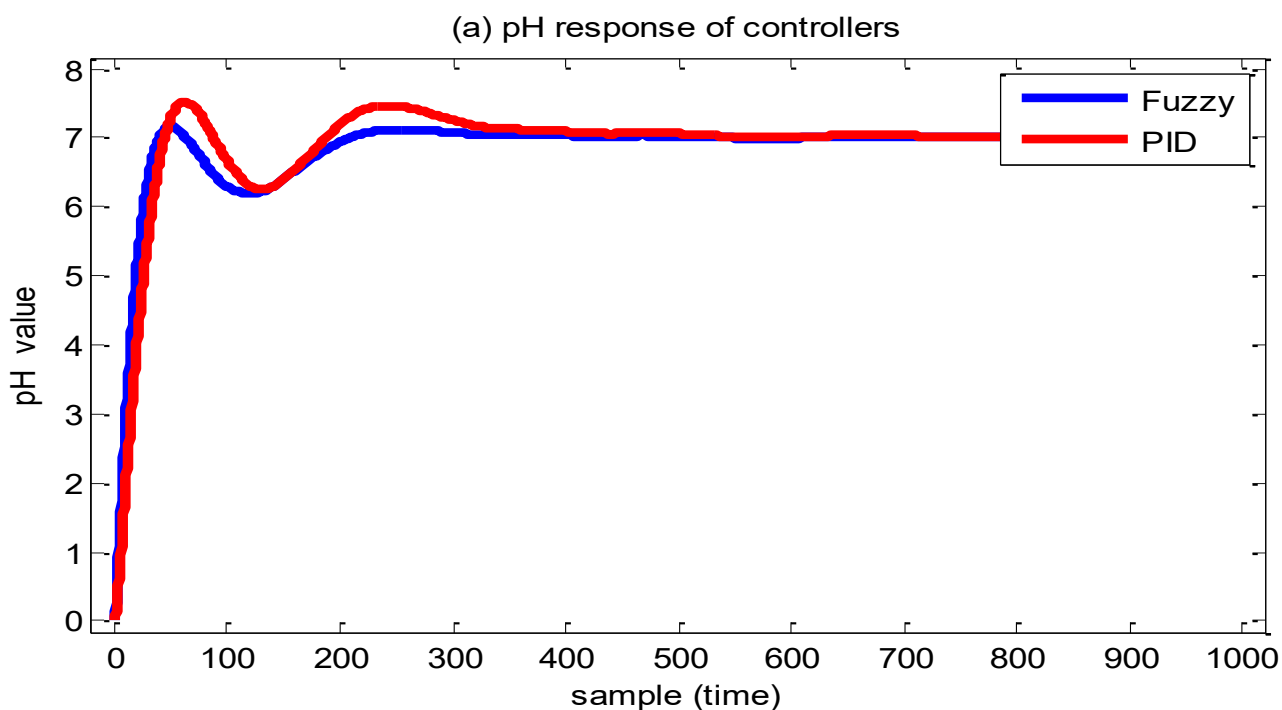
FLC demonstrates superior regulatory performance as indicated by values in Table 5.3. The FLC reduces the ISE by almost 23.58%. However FLC again outperforms PID by reducing maximum overshoot by 47.7%. Finally the FLC reduces the settling time by 16.67% in comparison with PID controller when process is subjected to disturbance of 20% acid flow rate.

Table 5.3: Acid flow rate Disturbance Rejection – Comprehensive Performance Analysis of all Closed Loop Configurations for pH Neutralization Process

Control Schemes	Over shoot (Sec)	Time taken to anticipate the disturbances (sec)	Set point (pH value)	average Integral Square Error (ISE)
Fuzzy	3.37	27.58	3	2.23
	1.5	635.5	7	

PID	7.34	33.33	3	3.743
	3.27	287.2	7	

As shown in Figure 5.5, the simulation result shows the capability of the fuzzy logic controllers when there are disturbances in the concentration of the acid solution. The idea of this exercise is to observe whether or not the fuzzy logic controls are able to maintain the pH value at pH set point regardless of the disturbances in the concentration of the acid solution. In this case the concentration of acid is decreased while the concentration of alkaline will be kept to a constant value. The method used to decrease the concentration may be filling in the tank with more water (i.e. a dilution process). At the same time the acid solution was stirred manually to ensure as near perfect mixing as possible in the solution.



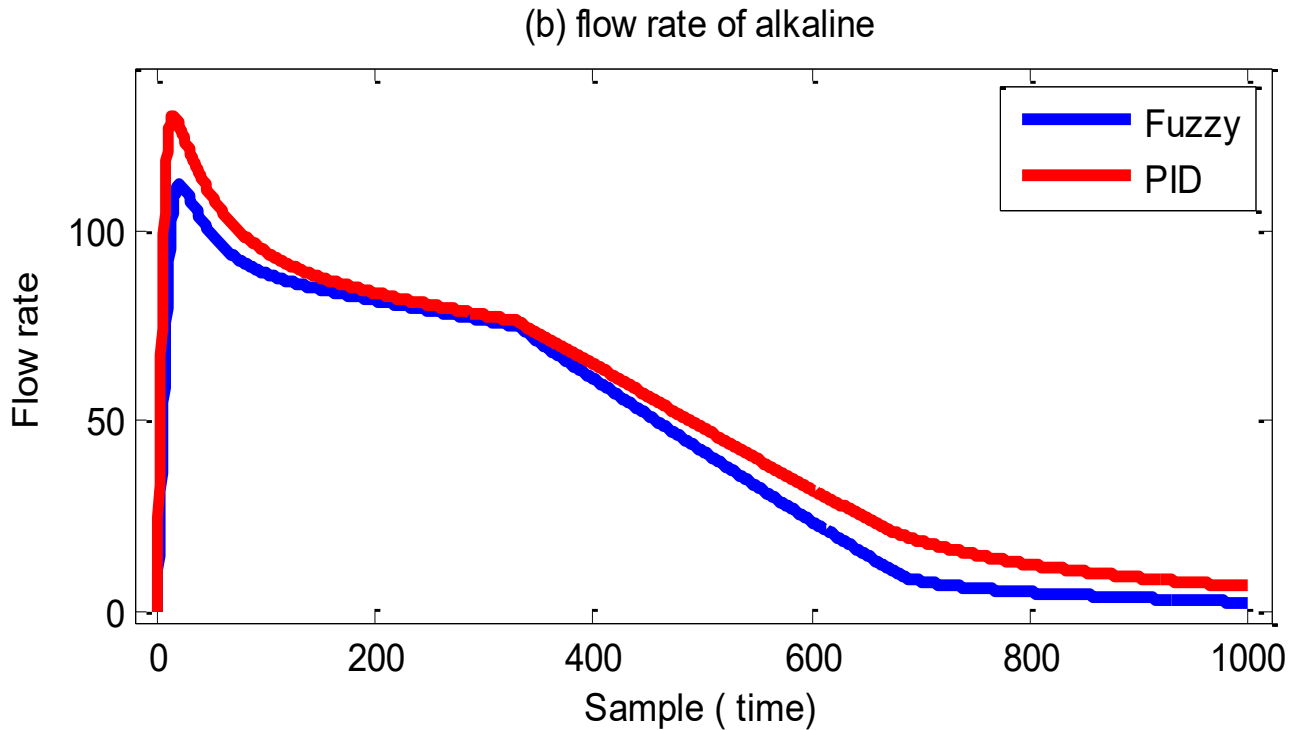


Figure 5.5: Simulation results for acid concentration disturbances with PID Controller and fuzzy controller in pH Neutralization Process.

The expected response from the alkaline stream involves a reduction of flow rate. This is because the concentration of the alkaline solution becomes larger compared to the concentration of acid. Based on the balanced

As we see in figure 5.5 the result the auto-calculated set point for alkaline flow will also decrease in order to reduce the alkaline flow rate. The fuzzy logic controllers are capable of maintaining and controlling the pH value at its set point value than PID controller. And also the flow controller step down slowly in fuzzy control. Once again it shows that the fuzzy logic controllers are reliable and able to perform their task within the required performance specification.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

This study is concerned to develop a dynamic nonlinear pH neutralization process model and to design and evaluating a suitable controller on wastewater treatment process. This main objectives have been achieved.

The development of a dynamic nonlinear pH neutralization process model is based on the use of physical and chemical principles and fundamental laws, using a conventional mathematical modelling process, coupled with information obtained from kilinto brewery WWTP daily report. This physico- chemical modelling approach is a rigorous and generally applicable method of deriving dynamic equations for a pH neutralization process using a type of representation based on the concept of a continuous stirred tank reactor (CSTR) model.

Conventional control strategies for pH neutralization are based on feedback of the pH measurement, even knowing that the pH is highly non-linear concerning the manipulated variable. As a result of this non-linearity, the process gain may vary over a large range of values, which is nowadays compensated through the use of non-linear controllers. The PID controller has shown a weak performance when submitted to load disturbances and set point change. Its application is not recommended when dealing with great load changes. Thus the control performance of the PID controller may be used as a point of reference for other control approaches to the problem of control of the pH neutralization in wastewater plant.

Design and implement an intelligent or advanced controller, based possibly on a Fuzzy Logic Control approach, involving use of an appropriate controller structure. There are two different types of controller; the flow controller and the pH controller. These controllers are actually both designed using a fuzzy logic approach. The design for the flow controller will depend on the characteristics of the valve that is controlling the particular stream or flow. In the case of the pH controller the dynamic reaction of the acid - base neutralization process is of crucial importance in the design.

In order to verify the reliability and performance of the controllers several types of computer-based simulations had been performed. Each simulation result gives specific information about different aspects control strategy. In comparison with PID, the FLC demonstrates superior performance as

indicated by values in tables' ((5.1), (5.2), and (5.3)). The fuzzy logic controller reduces the ISE by almost 31.74% in average. Both controllers shows worst performance when the pH set point at initial value 3. However FLC again outperforms PID by reducing maximum overshoot by 55.6%. Finally the FLC reduces the settling time by 14.37% in comparison with PID controller in average.

The investigations on the performance of the fuzzy logic control combined feedback controller structure has been shown to be capable of providing good control performance in terms of set-point tracking, disturbance rejection, and robustness compared with a conventional proportional plus integral plus derivative controller.

6.2 Recommendation

The controller described here was designed for use with a single-input single-output process. This is not a limitation of the fuzzy logic controllers. So, further work should consider the design and implementation of multi-variable fuzzy controllers to test their performance on multi-input and multi-output real processes.

The problems in pH control systems are caused by two kinds of disturbances mainly: changes in the feed flow and changes in the feed flow composition. The first type is, in the industrial applications, often regulated by feed forward control. The second type is more difficult to control, because it can displace the titration curve and change its format. Thus, an investigation on how to know these compositions and different types of acid and alkaline would react and behave with this control approach has to be a further recommendation for future work.

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Appendix

Appendix A. Process flow

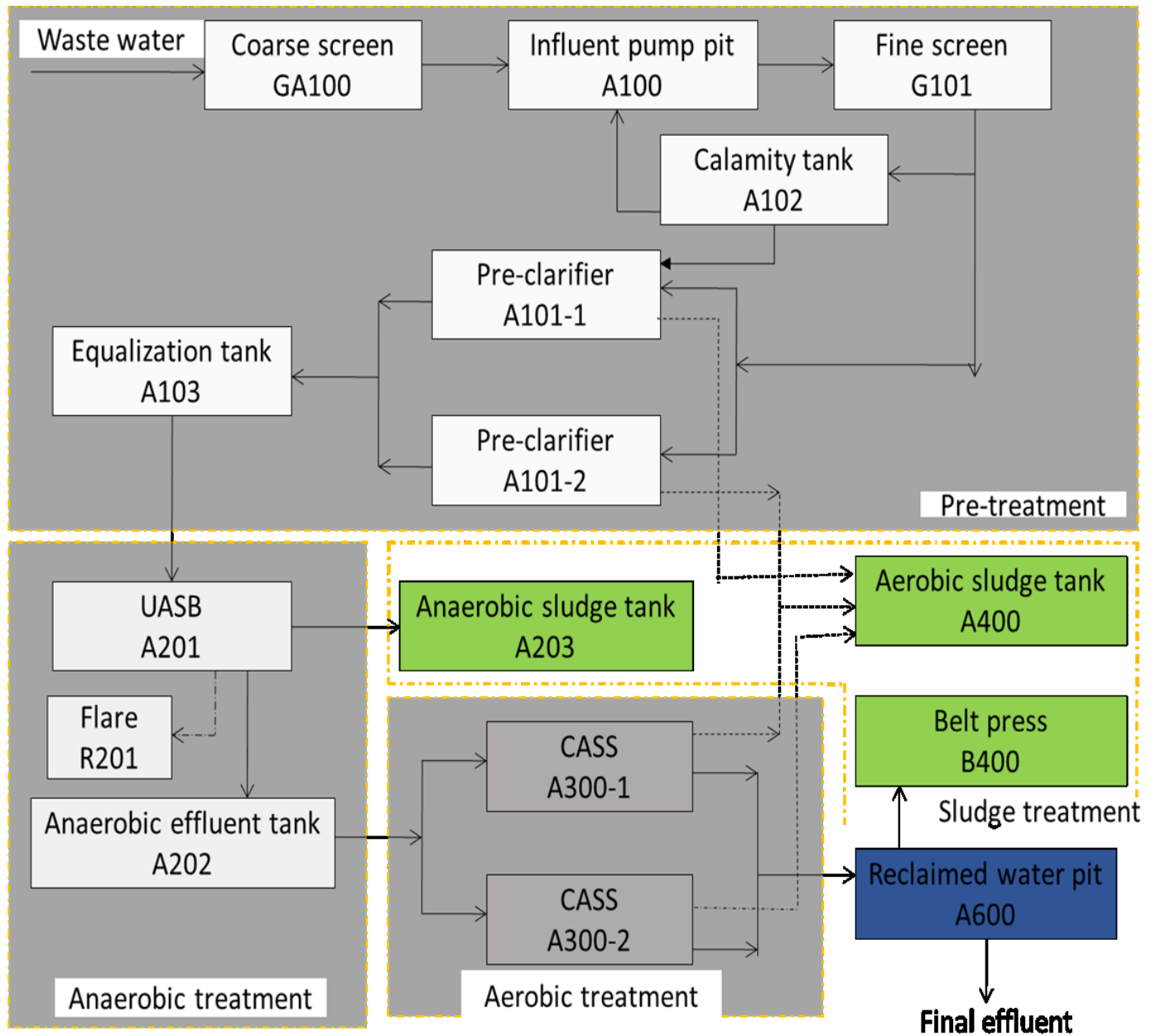


Fig WWTP process flow chat

Appendix B. Wastewater characteristics

Table B-1 Influent characteristics are according to the inquiry specifications

Parameter	Units	Wastewater quantities and loads*	
		Maximum [#]	Average
Waste water quantity	m ³ /day	1,900	-
Peak flow (before equalization)	m ³ /h	120	-
Flow after equalization tank	m ³ /h		80
COD-load	kg/d	5,700	4,000
Concentration COD	mg/l	3,000	2,100
BOD ₅	mg/l	1,800	1,300
Total suspended solids	mg/l	500	300
N-tot [^]	mgN/l	80	50
P-tot [^]	mgP/l	30	20
Temperature	°C	Range: 25 - 38	34

Appendix C. WWTP daily report

Table C-1 Data from PLC

Analysis to be filled in by operator

Date	pH	Flow rate	Feed flow	In-line pH1	TEMP
	3-7	<80	< 1,900	5-9	< 40
	pH103	F103-1	F103-1	pH201-1	°C
	sampler	m ³ /h	m ³ /d		
	D	D	D	D	D
Freq.	6.5	0	0	6.54	28
1-20	5.6	0	2	8.56	28
1-21	5.8	5	63	7.12	28
1-22	5.5	5	112	6.35	31
1-23	5.8	10	230	6.4	31.5
1-24	3.35	10	225	6.37	31.5
1-25	3.65	8	195	6.27	32
1-26	3.94	10	230	6.94	32
1-27	4.25	13	300	6.46	32
1-28	4.15	12	290	6.69	32
1-29	4.7	13	300	5.87	32.1
1-30	4.47	13	320	5.9	32.4
1-31	4.67	15	365	6.08	32.1
2-1	5.06	15	300	8.41	32.2
2-2	4	15	210	7.38	32.4
2-3	4.36	15	360	6.55	31.8
2-4	4.4	15	318	5.46	32.7
2-5	5.18	20	362	6.4	31.6
2-6	5.46	20	460	5.8	32.5
2-7	5.8	25	514	7.19	32.8
2-8	5.4	30	698	6.4	32.5
2-9	5.6	35	828	6.65	32.4
2-10	5.6	35	820	6.41	32
2-11	6.1	40	942	6.55	32.1
2-12	3.35	40	864	7.78	32.1
2-13	3.65	40	894	7.5	32.2
2-14	3.94	40	974	7.78	33.8

2-15	4.25	44	1066	6.76	31.7
2-16	4.15	44	1056	6.21	32.5
2-17	4.7	48.5	1164	6.1	32
2-18	4.47	55	1250	6.47	33.3
2-19	4.67	61	1320	6.5	33.2
2-20	5.06	61	1442	6.55	33.5
2-21	0	60	1431	6.75	33
2-22	6.07	66	1637	6.75	34.5
2-23	6	70	1684	6.73	31.7
2-24	6.1	70	1659	6.23	32
2-25	6.7	70	1725	6.35	33.5
2-26	6.6	70	1687	6.35	33.5
2-27	5.7	70	1686	7.3	33.2
2-28	5.8	70	1681	9.02	32.5
3-1	5.2	70	1529	8.17	33
3-2	5.2	60	1059	7.88	33.6
3-3	6.4	60	1115	7.32	34.5
3-4	6.4	80	1679	6.99	35.2
3-5	6.36	80	1912	7.04	33.1
3-6	6.5	80	1920	7.04	32
3-7	6.5	80	1960	7.76	30.8
3-8	6.6	40-80	1280	7.09	31
3-9	5.4	79.9	1917.6	6.62	34
3-10	5.48	80	1917.6	6.72	33
3-11	5.65	100	2104	7.18	34
3-12	6.15	80-85	2007	7.54	32
3-13	6.5	80	1921	7.5	35.5
3-14	7	80	1880	8.52	31.8
3-15	6.66	62	1452	7.96	33.3
3-16	7	79	1818	7.77	32.7
3-17	6.37	80.1	1961	7.93	34.3
3-18	6.08	79.9	1895	7.56	32.7
3-19	6.35	80	1316	6.91	33
3-20	8.45	80	1834	5	32.7
3-21	7.08	65	1247	1.62	31.9
3-22	6.4	59.7	791	6.11	32.2
3-23	7.64	49.4	1805	6.63	33.5
3-24	7.2	80	1817	9.24	33.1